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SECOND-LIFE SOLUTIONS FOR END-OF-LIFE PHOTOVOLTAIC MODULES

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SECOND-LIFE SOLUTIONS FOR END-OF-LIFE
PHOTOVOLTAIC MODULES

BY

LENNART BANASZAK

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF
THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE

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MASTER OF SCIENCE
OF
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ABSTRACT

Solar energy provided by photovoltaic (PV) panels experiences significant and continuous growth and makes solar energy a major contributor to renewable and sustainable energy worldwide. However, there are always two sides to the coin. A proper end-of-life management for PV panels is crucial to keep solar energy sustainable and environmentally conscious. This thesis investigates second-life potentials for used PV panels and supports that idea by analyzing reasons for skyrocketing amounts of discarded PV panels.

First of all, basic knowledge about PV panels is provided. Afterward, the solar energy market in the U.S., and especially New England, is analyzed, and current recycling or disposal strategies are stated. Next, it is demonstrated how recent trends of costs and innovations in the case of PV panels could lead to economic considerations about PV panel replacements before reaching their technical end-of-life. A break-even analysis for the replacement is reported. Furthermore, experiments with used PV panels are conducted to investigate the sectioning of PV panels, and a particular second-life use case is proposed. Finally, a mathematical optimization model is programmed to find cutting strategies for the cutting of PV panels.

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ABBREVIATIONS

Abbreviation	Description
2D BPP	Two-Dimensional Bin Packing Problem
2D CSP	Two-Dimensional Cutting Stock Problem
BOS	Balance of Systems
C&P	Cutting and Packaging
DEEP	Department of Energy and Environmental Protection
EOL	End-of-Life
EPBT	Energy Payback Time
EVA	Ethylene Vinyl Acetate
Fraunhofer ISE	Fraunhofer Institute for Solar Energy Systems
GWP	Global Warming Potential
ILP	Integer Linear Programming
IRENA	International Renewable Energy Agency
ITC	Investment Tax Credit
LCA	Life Cycle Assessment
MACRS	Modified Accelerated Cost Recovery System
Maine DEP	Maine Department of Environmental Protection
MassDEP	Massachusetts Department of Environmental Protection

NERC	Northeast Recycling Council
NHDES	New Hampshire Department of Environmental Services
PV	Photovoltaic
PVC	Poly Vinyl Chloride
PVF	Poly Vinyl Fluoride
RIRRC	Rhode Island Resource Recovery Corporation
SEIA	Solar Energy Industries Association
VT ANR-DEC	Vermont Agency of Natural Resources Department of Environmental Conservation

Chapter 1

1 Introduction

For waste management of photovoltaic (PV) modules, the commonly known 3R's – Reduce, Reuse & Recycle [1] can be applied. “Reduce” is managed by current research and development activities to reduce the amount of each raw material needed [2], and “Recycle” is mainly done as bulk recycling by focusing on glass and aluminum. The “Reuse” part of the 3R's has not been given much attention so far - there are hardly any current articles dealing with a reuse approach. This master thesis investigates the potential for second-life solutions of used PV modules. PV modules are also usually referred to as PV panel, solar panel or solar module.

1.1 Statement of the Problem and Significance of the Study

Photovoltaic is a significant contributor to the global renewable energy transition. Currently, the U.S. is with 88.9 GW, the second-largest PV market after China of total installed PV energy capacity at the end of 2020 [3]. Recent studies forecast the global solar energy power to grow to 600 GW in 2050 [2]. As only 25 GW of solar energy was installed in 2015, there is enormous and continuous market growth. With a technical lifetime of 25-30 years (depending on the manufacturer), significant amounts of end-of-life solar modules are expected to reach their end-of-life from 2025 on. By 2030 the cumulated e-waste volume will hit 200,000 tons and grow to seven million tons in 2050. [2] But, many PV modules are sent to recycling or waste disposal before they have reached their technical end-of-life as utility-scale solar farms and other solar systems could be repowered early. That might have different reasons and will be investigated within this study. In addition,

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even damaged solar panels or solar panels that have reached their predicted end-of-life can still convert the sunlight into electricity [4]. Further, as most PV modules in the U.S. end up in landfills, still working PV modules probably end up in landfills [5]. Instead, the most sustainable option for still working PV modules will be a proper second-life solution. As there are hardly any current articles concerning second-life approaches for PV modules, this research area might be underestimated. Second-life PV modules will still have a sufficient degree of efficiency left and will be an important opportunity for customers with limited financial resources. [2] On the other hand, there might be applications for PV panels that differ from the commonly known rooftop or utility-scale solar farm case. For example, different sized solar panels can power several electric equipment and infrastructure like street lights, 5G antennae, or other small electric infrastructure equipment [6] as they do not need the wattage of a standardized PV module. Additionally, there might be applications requiring individual-sized modules that are non-economic to produce.

This study investigates the feasibility of repurposing standard-size solar panels by cutting them into individual sizes. Additionally, the applicability of cutting stock heuristics for the underlying cutting problem is examined.

The investigation about second-life solutions also has significant value for the Rhode Island state. There is a high growth of solar energy due to outstanding incentives even though Rhode Island is a tiny state [7]. Concerning annual installation rates, Rhode Island was on rank 17 in 2019 and 25 in 2020 within all United States [8]. Hence, there will be high volumes of solar panel e-waste in the future, even in Rhode Island.

1.2 Methodology

Several investigations of different topics are necessary to achieve the objective of this master thesis study. Hence, the study is structured into four main parts.

First of all, a brief literature review is given to introduce PV panels from a historical, technical, and end-of-life perspective. Additionally, brief insights into PV energy's sustainability are shared. Afterward, a literature review for cutting stock heuristics is reported while firstly focusing on general approaches and secondly on a deep dive into two-dimensional cutting stock algorithms.

The literature review following chapter 3 – the market overview – provides facts about the solar energy market development in New England on the one hand. On the other hand, insights about Rhode Island's current solar panel recycling structure and regulations are described and compared to the remaining New England states. Additionally, a selection of non-profit organizations and solar energy waste-related companies is illustrated. Chapter three ends with the investigation of various imaginable second-life use cases and potential regulations.

In Chapter four, the study's primary investigations are presented. Firstly, the general approach is illustrated to repeat the objective mentioned in section 1.1. The second section provides facts to support the second-life need for solar panels. A break-even analysis is reported that investigates the economics of solar panel replacements. Several conclusions from that spreadsheet calculations are drawn. Afterward, the experimental part of the study is described, and the findings of various experiments are reported.

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The study continues with a detailed description of a two-dimensional cutting stock algorithm's methodology and its application on solar panel cutting. Further, the program's implementation in Python is explained.

Finally, conclusions are drawn in the closing chapter and some ideas for further investigations are discussed.

Chapter 2

2 Literature Review

The second chapter provides basic theoretical information about the thesis's two main components – photovoltaic panels and the cutting stock approach. A literature review offers a deep dive into those topics.

2.1 Photovoltaic Panels

Photovoltaic panel (PV panel) is a general term for a self-contained system that can convert light into electricity by harnessing the photovoltaic effect (PV effect) within the semiconductor material. Another common term for PV panel is “solar panel”. The light's photons traveling through the semiconductor structure hit the electrons and causing them to cut loose from their atomic bonds. That creates a flow of electrons within the semiconductor structure, resulting in a measurable electric potential. Connecting a load to the cell's negative and positive pole results in an electric current. [9]

The following sub-chapters give a brief overview of the historical evolution, the design and manufacturing, and state-of-the-art recycling methods of PV panels.

2.1.1 History of Photovoltaic Technology

The first time, the PV effect was observed was back in 1839, by Alexandre Edmund Becquerel, a French physicist. Roughly one hundred years later, in 1954, the first useable PV device was invented and introduced by Bell Labs in the U.S. and applied in small commercial and scientific use cases. The solar panels entry into the energy market to power homes and businesses was in 1970 and thrived due to the then emerging energy crisis.

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Ongoing research and development in the following decades made prices for solar energy plummeted as they were at least 30 times higher in the 70s then today. [10] Additionally, the efficiency strongly increased and due to the need for renewable energy to counteract the climate change solar energy have become a substantial contributor to the global renewable energy mix. [11]

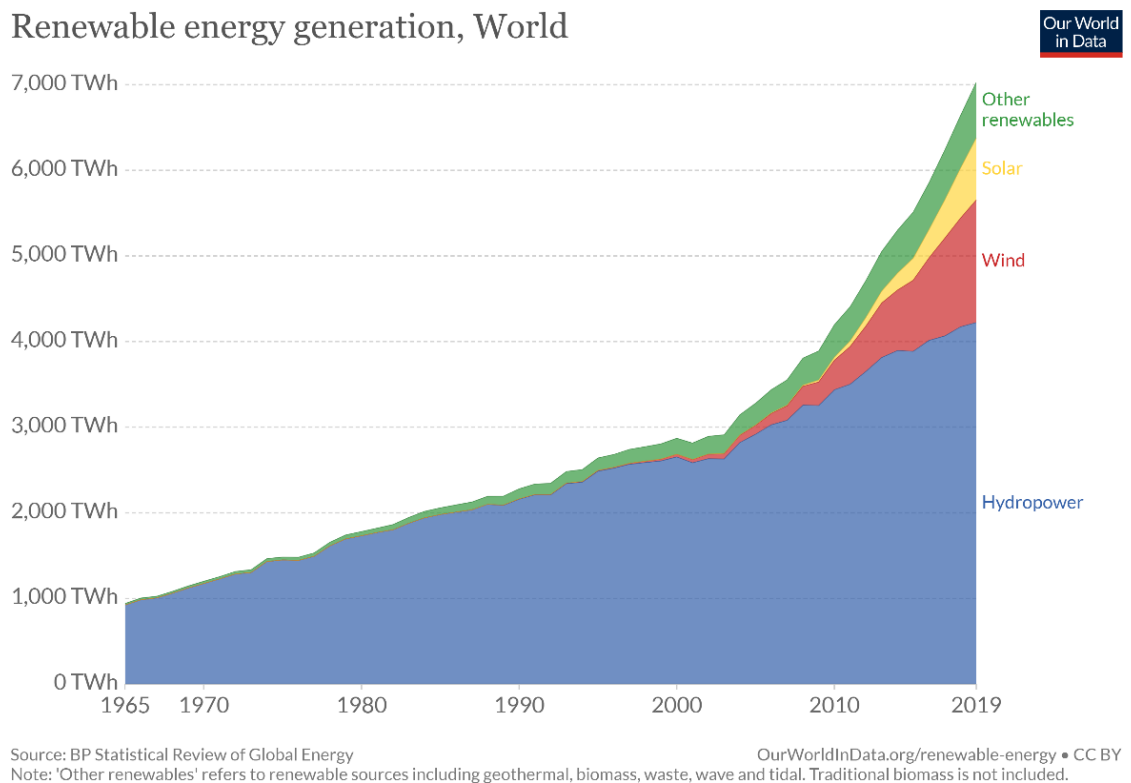


Figure 2-1: Global Renewable Energy Mix [12]

Referring to the figure above, the energy portion generated by solar modules is enormously increasing since 2010.

Figure 2-2 shows how the efficiency of different solar module technologies has developed over time from 2006 to 2018. That particular figure was published by the

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Fraunhofer Institute for Solar Energy Systems (Fraunhofer ISE) and is limited to the average efficiency of crystalline silicon solar panels.

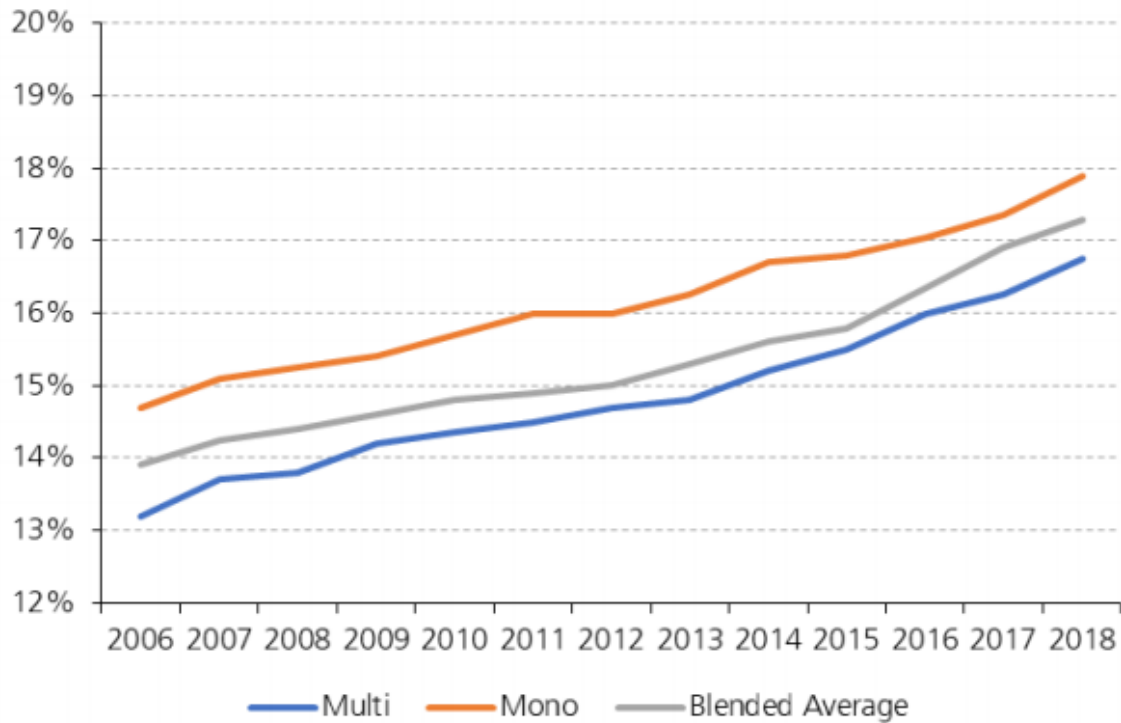


Figure 2-2: Efficiency Development of Crystalline Silicon Solar Panels [13]

That values within figure 2-2 must not be confused with the efficiency measured in laboratory conditions. In that case, much higher efficiency values are achieved, as figure 2-3 shows.

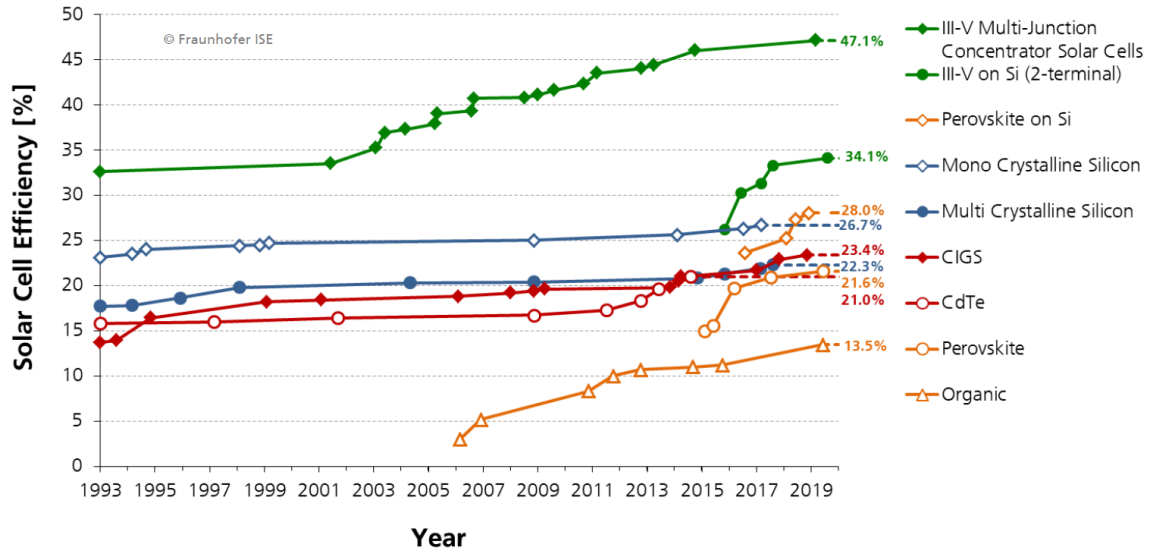


Figure 2-3: Development of the Efficiency measured in Laboratories [13]

The most common technologies are described in the following subchapter.

2.1.2 Design and Manufacturing

First of all, there is an enormous pool of solar panel types that mainly split into two groups: thin-layer solar cells and crystalline silicon cells (c-Si). The secondly mentioned type divides into several subtypes, including primarily mono-crystalline and multi-crystalline cells. [14] Those types of solar cells are commonly used for residential or commercial rooftop solar systems and represent the significant share of solar panels on earth – 95% in 2019 globally, referred to the 2020 photovoltaic report prepared by Fraunhofer ISE. [13] For this reason, the article will focus on crystalline silicon solar panels and, more precisely, those standard-size panels that are used for rooftop systems and solar farms.

Thin-layer solar cells and all their subtypes are used for small devices like pocket calculators or garden lights, for instance. [14]

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The critical element – silicon – is one of the most abundant elements on earth. Though, it never appears in its pure form but mainly in silicon oxide (SiO_2). To receive pure silicon, there are two main processes. In the first phase, high-quality silica containing a high portion of SiCO_2 is reduced with carbon in an arc furnace at about 1,800 C to break the oxygen bonds. The second phase removes elements that are still contaminating the liquid silicon. There are different methods for the second phase available, making it too extensive to describe in this study. More information can be found here: [15]. Finally, polysilicon (same meaning as multi-silicon) with a purity up to 99,999999% is obtained. [15] It can either be directly cast into ingots from which the wafers can be cut or be preprocessed to monocrystalline silicon. Wafers from monocrystalline silicon have higher efficiency. [16]

Even though there are also reams of different panel types within the crystalline silicon panels group, the basic construction principle is always the same. 36 to 96 silicon cells are lined up in a rectangular shape and electrically connected to a string to receive a total power outcome from 100 to almost 450 watts depending on the module's individual power and size. [17]

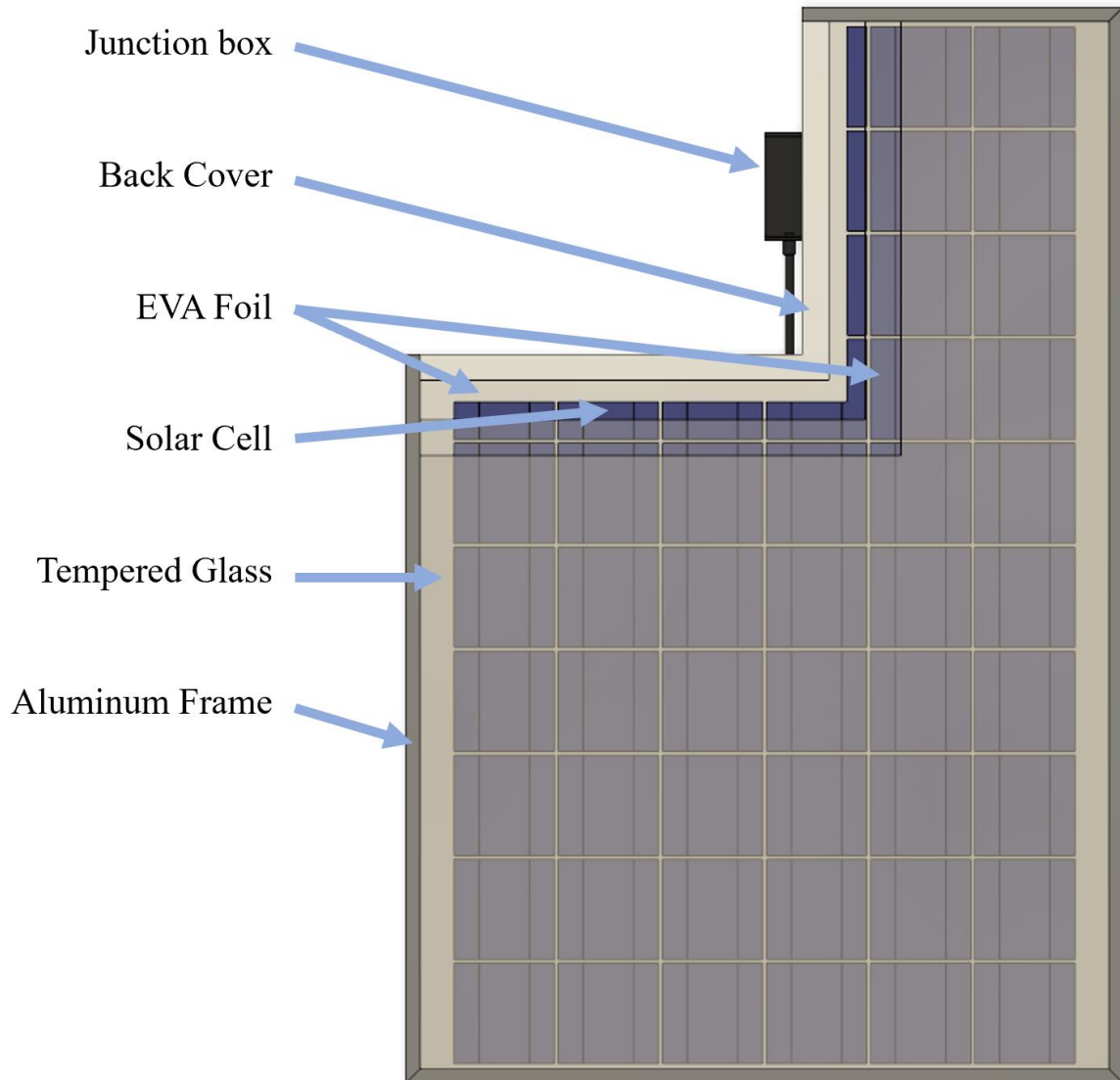


Figure 2-4: A Solar Panel's Principal Design

One cell is primarily made of crystalline silicone [15] supplied with tiny silver conductor fingers and more oversized, so-called bus bars made of silver and copper (see figure 2-5). The conductor fingers collect the electrical current from the cell and conduct it to the bus bars. They connect the cells to one string. The string of cells is laminated between two layers of EVA (ethylene vinyl acetate) foil and covered by tempered glass on the upper side and some kind of back cover on the lower side – in most cases PVF (polyvinyl fluoride). This multi-material sandwich, as shown in figure 2-4, generates high

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encapsulation from environmental impact. Significantly, the tempered glass offers strong protection against physical effects and strong weather conditions while improving the stability of the whole module. The sandwich is framed with extruded aluminum profiles for stability reasons and has a junction box on the lower side connecting to the entire solar system. [18]

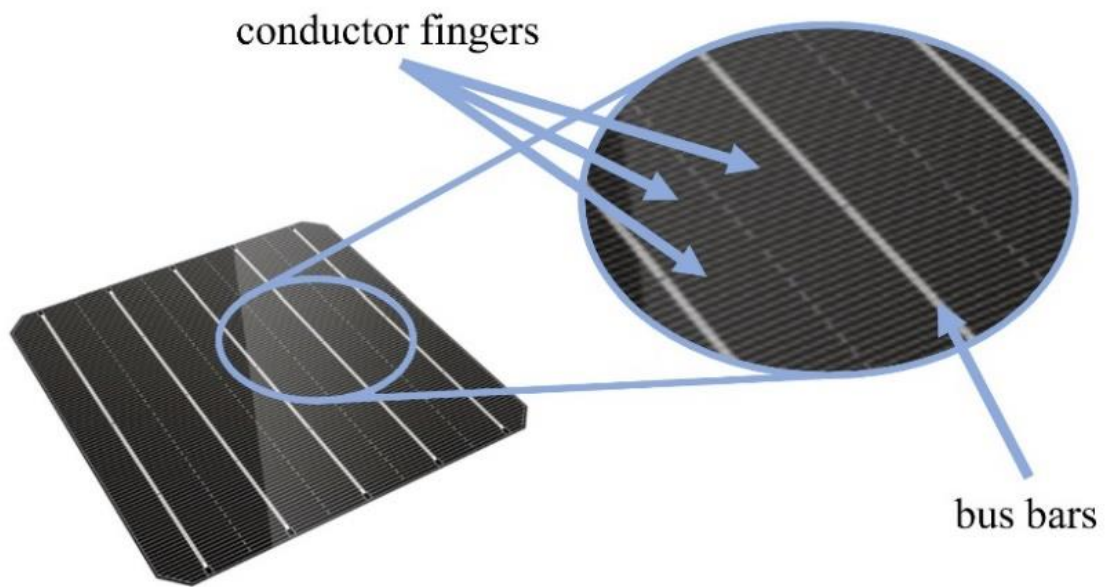


Figure 2-5: Conductor Fingers and Bus Bars on a Solar Cell

The following table shows all materials assembled, including their weight share in the entire module (weight of typical module is about 18.5 kilograms):

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Table 2-1: Material Overview within a Standard Crystalline Silicon Panel [14]

Material	Weight in percent [%]	Absolut weight per module [g]
Glass	74	13,700
AL frame	10	1,850
EVA encapsulation	6.5	1,210
Back cover (PVF)	3.6	660
Copper	0.6	110
Silicon	3.5	640
Zinc + lead (soldering)	0.19	35.2
Silver	0.006	1.11
Silicon glue, etc.	1.16	214.6

Glass has by far the highest weight share. Hence, state-of-the-art recycling is mainly done by glass recyclers and manufacturers, as recovering the glass is also the most effortless process. To create highly efficient solar panels, solar glass has to be more transparent than glass commonly used for windows, for instance. Solar panel glass, therefore, needs a low-iron ratio. Adding the aluminum to the amount of glass, already about 84 % of a solar panel's weight is covered. Those materials are well recyclable by conventional recycling technologies like crushing and sorting and can be melted and formed into new products afterward. However, as the glass gets contaminated during the shredding process, it cannot be recycled as float glass. Most of the recycled glass returns as a compound in construction materials or reflective paint. [19]

The EVA for the encapsulation and the back cover, mainly made of polyvinyl fluoride (PVF, known as TEDLAR as DuPont's trademark) [20], add up to another 10 percent of the material used for a solar panel. The most valuable materials that are the productive part within a solar panel – silicon, copper, and silver – are only responsible for minor percentages.

2.1.3 Reasons for the Disposal of Solar Panels

There are several reasons for solar panels to be discarded. First of all, physical impacts caused by wind, hail, or, for example, falling branches due to intense weather conditions can cause damage. [21] The tempered glass is strong, but the whole glass sheet will shatter into tiny pieces if it gets damaged. [22] Those pieces at least will not fall apart as the sticky EVA keep the panel's structure alive. But the panel loses its impermeability, and further damage will occur. Besides, technical damage within the cells due to electrical function might occur. [21] That occurring damage can destroy the whole panel, only certain areas, or single cells (see chapter four).

Another motivation to update a solar system with new solar panels can have its origin in the panels' efficiency. On the one hand, a solar panel has a continuous performance decline of about 0.5% to 3% per year. [23] This decline is mainly caused by thermal cycling, damp heat, humidity freeze, and UV exposure. Thermal cycling, for example, can lead to cracks or bond failure of conductors within the panel, and UV exposure can make the encapsulant yellow. However, the use of better materials will counteract such effects. [21] On the other hand, inefficiency occurs compared to new solar panel types, as innovation leads to increased efficiencies. Figure 2-1 in section 2.1.1 shows the efficiency development of different solar panel types. Especially the second aspect has a crucial role in e-waste generation from end-of-use solar panels. On average, investments in solar farms are paid back after seven years, and the solar system might be renewed after another five years of operation. Hence, the discarded solar panels could be about twelve years old and still in good condition. [5]

In addition, some studies show a much smaller performance degradation of PV panels than the degradation mentioned above. In one particular study, solar panels produced in 1976 still had a performance of 96 % in 2015. As manufacturing technology has improved in the past years and will further improve in the future, solar panels will probably last up to 40 years. [24] That leads to the fact that a vast portion of discarded solar waste is not waste at all. Those used panels, for example, could be sold to developing countries at a lower rate and help ramp up the renewable energy share besides the industrialized countries. [2] Whether there might be other second-life approaches will be investigated within this study.

2.1.4 Challenges in the Case of a Solar Panels End-of-Life

End-of-life (EOL) management is an important field. It covers what happens to a commodity at end-of-use, could advise design criteria to receive improved recyclability, and is a crucial discipline to achieve a circular economy. [25] As mentioned before, solar panels are designed to be resilient against environmental impacts for about 25 years. That is mainly achieved by the laminating procedure connecting the various layers of materials to one solid sandwich. The laminating makes it significantly challenging to separate the materials at the panel's EOL. In fact, the fundamental design did not change over time, as long-life durability might be more critical than recyclability. Nevertheless, solar panels can be recycled, and most of the materials used have good recyclability.

Today's most common recycling approach is bulk recycling. Glass recyclers mainly do this as glass has the main weight proportion within a solar panel and is proportionally well recyclable. [26] Within the bulk recycling approach, the material sandwich is separated from the aluminum frame and the conjunction box in the first place. The

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aluminum is directly sold as aluminum scrap metal and easy to recycle. The conjunction box is a small electronic device with a polymer housing that is recycled like other e-waste. The remaining sandwich of glass, EVA, silicon, conductor metals, and PVC is shredded and sorted into its compounds by state-of-the-art sorting methods like optical sorting. [27] Other approaches focus on chemical treatments or melting with subsequent electrolysis to separate the compounds. [28]

This approach is challenging regarding the purity of its outcome as it is difficult to separate the highly adhesive EVA from the glass and silicon wafer. Further, the conductor fingers are screen printed onto the silicon wafer and very thin. Those conductor fingers cannot be removed within the bulk recycling, and the most valuable material within solar panels – silver – is lost. For this reason, current research is focusing on other recycling approaches. The German startup SOLAR MATERIALS [29] focuses on an abrasive approach to separate the materials more properly.

Other approaches focus on taking apart the solar panel sandwich while neither destroying the glass nor the fragile silicon wafer. [30] That is done by heating the entire solar panel in a furnace at 500°C for one hour. It makes the EVA evaporate. As a result, the glass can be removed in one piece, and the silicon wafers can be easily reused. But the process consumes a lot of energy, and harmful gases are emitted. Thus, it is not possible to run it economically. Another approach focuses on a chemical solvent to make the EVA melt and disappear. Unfortunately, it takes about ten days and vast amounts of organic solvents, making the entire approach uneconomic. [30]

The described challenges show a significance in reusing and repurposing solar panels as the effort would be much lower. The idea and methodology will be described in chapter four.

2.1.5 Brief Excursion into Life Cycle Assessments (LCA) for Solar Panels

Crystalline PV panels are well studied in the case of LCAs. Most LCAs are conducted with boundaries reaching from production (including raw material extraction) to use and some to end-of-life. Hence, the transportation effort for raw materials and the finished product is included. Nevertheless, results heavily vary based on different module types, energy mix within countries, and transportation distances. [31] Further, it is untransparent whether approaches include the transportation of the final solar panel only or also the parts' and materials' transportation. A distribution overview of the world manufacturing of polysilicon for solar cells shows that the U.S., Germany, and South Korea are major polysilicon producers while only minor manufacturers of solar cells and entire panels. [32]

One study compares the carbon footprint of U.S.-made and China-made photovoltaic modules that have to be installed in the United States. It turned out; fully U.S.-manufactured modules are 13 to 21 percent better regarding their carbon footprint, which is smaller than expected. That difference is caused by the countries' varying energy mix and logistical efforts. [32]

Another important and non-negligible aspect for solar energy systems are the equipment additionally needed to create a solar system, usually referred to as the “balance of system” (BOS). [31] BOS is a term for all needed items within PV power generation systems besides the solar modules themselves. It includes inverters, controllers, junction boxes, wiring, array support, and sometimes electricity storage systems. A storage system

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with batteries has the highest impact on all BOS components. But most PV power generation systems do not have a storage unit. The second-largest impact comes with the array support, the supportive construction to mount the solar panels on the ground or roofs. Based on the mounting approach, impact numbers are highly varying, as the volume of required construction materials like steel and concrete differ. [33] In the end, several studies showed the non-negligibility of BOS components within LCAs. [31]

Furthermore, the LCA review paper [17] reveals the lack of end-of-life management within most studies. That might not be a problem as the energy used to recover resources from used panels is considered in LCA studies of solar panels that contain recycled materials. Besides, it is questionable whether the disassembly and transportation of old panels are considered or not. Nevertheless, there is a lack of regulations for the disposal of solar panels in most countries, leading to most solar panels probably ending up in landfills. [34] This environmental impact should definitely be included within LCAs.

Within LCAs, the product's embodied energy plays a specific role. The embodied energy is the energy that is needed to mine the raw materials and manufacture the product. This proportion is crucial for renewable energy technology to calculate the amount of time a product – the solar panel in this particular case – needs to repay the energy. This time is known as the energy payback time (EPBT) measured in years. [31]

The standard crystalline solar panel has an EPBT of two to four years, depending on the panel's efficiency that varies with the manufacturer and module type. The panel's increasing efficiency trend will lead to a future EPBT lower than two or even 1.5 years as some studies in [31] can already be considered outdated. With a typically guaranteed

lifetime of 20 to 30 years, the solar panel will pay back its embodied energy multiple times, making it highly sustainable from an energy perspective. [16]

Besides the most common EPBT approach, there are other important aspects included in a profound LCA. Those aspects are summarized in the category “Environmental Impacts,” which contains several potentials like the acidification potential, eutrophication potential, and the global warming potential (GWP) a product could have for the environment. The GWP can be determined by measuring the emitted greenhouse gases like carbon dioxide and methane in kgCO₂-equivalents per kWh, a standard unit within LCAs. [35]

2.2 Cutting Stock Problems

The Cutting stock problem is one particular problem within the general field of cutting and packaging (C&P), which started in the mid of the 19th century. The list reaches from cutting stock to trim loss problem, bin packing, knapsack problem, vehicle or pallet loading, line balancing, and many more. The primary objective is always similar and aims to generate an efficient layout of smaller geometrical pieces (items) within a larger geometrical object (stock object). With its variety, C&P is relevant in many disciplines. A few examples are Engineering Science, Information and Computer Science, Mathematics, and Operations Research. [36]

The cutting stock problem itself is mainly applied in production processes. Relevant industries are, among others, the clothing, furniture, automotive, and aerospace industry. [36] Due to those varying application areas, different types of cutting stock problems exist, mainly depending on the number of dimensions the problem has. As a result, there are one-dimensional, two-dimensional, and multidimensional forms. [37]

In the following, a brief introduction into the history of C&P is given before the relevant cutting stock problem for the solar panel study is investigated. After that, a typology for cutting stock problems and research that has already been done is described.

2.2.1 History of Cutting and Packing Problems

The history began around 1940 as the first mathematical papers dealing with C&P were published by Kantorovich (1939 Russian, 1960 English) and Brooks, Smith, and Stone (1940). [38], [39]

Within the 70s, Gilmore and Gomory introduced the first feasible techniques for medium-sized problems. They described a linear programming approach for the one-dimensional cutting stock problem using the column generation technique to create cutting patterns and solved it with the revised simplex method. Later, a solution for two or more dimensional cutting patterns is introduced that applies dynamic programming. Besides, they explained the computation of the knapsack problem and its importance in cutting stock problems. [37], [40], [41]

Later, many more approaches are published by authors like Christofides and Whitlock (1997), Wang (1983), and many more. [42], [43] Some of them will be described in more detail in subchapter 2.2.3.

As more and more approaches came up, the need for some overview evolved, and annotated bibliographies like Dyckhoff, Scheithauer, and Terno (1997) [36] were published. Further, the first typology for C&P problems was introduced as different names for the same logical problem created confusion within the research area. [44]

Research continued, and while some matured approaches were improved [45], [46], new interesting techniques were published. Some of them focus on particular use cases in the industry [47], other heuristical methods [48], or specific geometrical shapes [49].

2.2.2 Clustering of Cutting Stock Problems

In 1990, Dyckhoff introduced the first topology to cluster all existing and upcoming variations of C&P problems to decrease confusion by two or more names for the same logical problem. As this study focus on cutting stock approaches, the overall typology is not relevant. Nevertheless, Dyckhoff mentioned relevant and essential criteria to differ within the variety of cutting stock approaches. Those criteria are dimensionality, quantity (discrete or continuous), the shape of items, and pattern restriction. [44]

The dimensionality is the first and most important criteria as it sets the reference frame for the whole problem. The number of dimensions is related to the geometrical shape of the small and large items. The following types are imaginable: one-dimensional, two-dimensional, three-dimensional, and multidimensional. The last one considers all variations with more than three dimensions. [44] One-dimensional problems, for example, are relevant in the paper industry, where stock rolls of paper have to be cut into individual lengths. [50] The two-dimensionality is another prevalent situation as it deals with all cutting problems within one plane. Mostly rectangular cuts are considered to cut sheets of glass, plywood, or steel. However, the items' shape does not have to be rectangular, as another criterion shows later. [48] Three or more dimensions are not significantly relevant for the cutting stock approach but rather for packaging within containers or boxes. [44]

Referring to Dyckhoff, the way of measuring quantity is another important characteristic. The measurement could either be discrete with integer numbers or

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continuous with real numbers. [44] However, integer constraints are common in publications. [37], [43], [51], [52]

As already mentioned, the items' shape is a third criterion to distinguish between cases of application. Especially within the two-dimensional cutting stock problems, two general types of shapes exist. On the one hand, irregular shapes appear, for example, in the clothing industry to cut the fabric into pieces for shirts, pants, or any other clothes. On the other hand, regular shapes have a rectangular or any different kind of geometrical form. Those shapes mainly occur in the sheet metal, wood, furniture, or glass industry. [48]

Pattern restriction, another vital characteristic, refers to the way of cutting the material. Depending on the cutting machine or material restrictions, cuts can be made straight from edge to edge. That method is called guillotine cut or edge-to-edge cut. This way of cutting is popular within the glass industry. Without the edge-to-edge restriction, the cutting method is called non-guillotine cut, which is possible if the cutting machine can change direction while cutting. [44] One example could be a CNC laser cutter, as it can perform a freely chosen cutting path.

While placing rectangular items on a rectangular stock object, the item's orientation has to be considered. Hence, there is a fifth important criterion in addition to the four elements mentioned above. An item can be oriented so that its length is parallelly aligned to the stock object's length. In that case, the orientation is called "oriented," otherwise "not oriented." [53] This criterion mainly applies to the two-dimensional cutting stock problem.

While the orientation can be assumed as fixed and therefore act as a constraint, rotation can also be considered. However, in most research papers, items' rotation is excluded. [52]

In this study, the two-dimensional cutting stock problem (2DCSP) is applied. The following figure combines and summarizes all relevant criteria for the two-dimensional approach that have been described above:

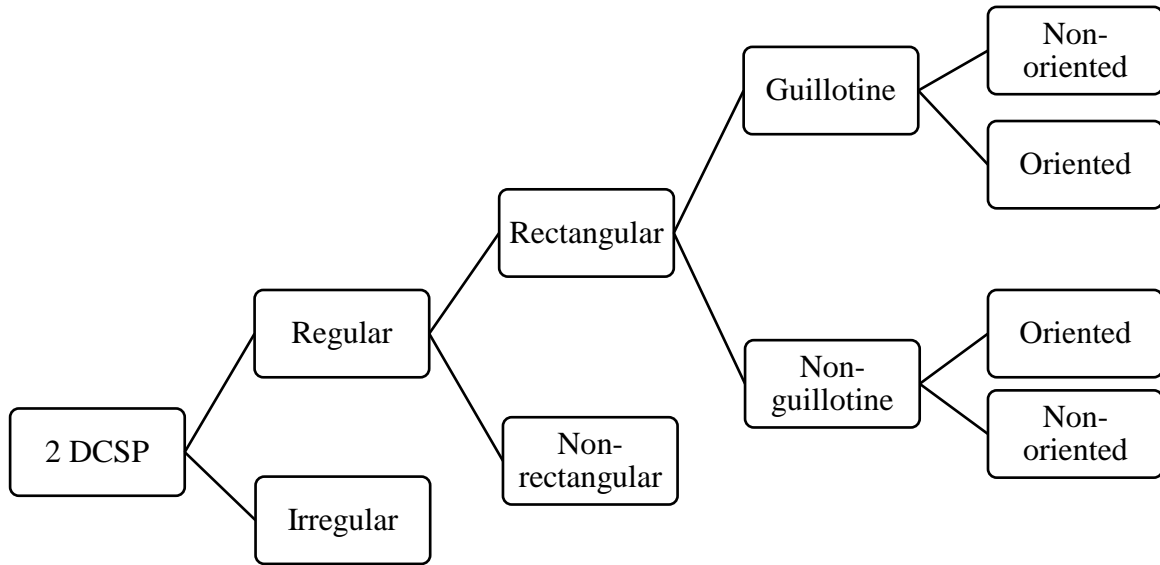


Figure 2-6: Characteristics for the Two-Dimensional Cutting Stock Approach (Figure based on [48])

2.2.3 An outline of developed approaches for the 2DCSP

This subchapter describes approaches for the 2DCSP that could be relevant for the cutting of solar panels.

As already mentioned in section 2.2.2, Gilmore and Gomory did some of the first publications concerning feasible and practical solutions for the cutting stock problem. They described a 2DCSP as a two-stage one-dimensional approach, with the knowledge from their first publication [40]. In the first stage, the stock rectangles are cut into strips with the width of the demanded items. Afterward, the second stage cuts the required length from the pre-cut strips. They use a column generation technique to limit the number of columns and rows that have to be considered for solving the linear programming approach. Each column corresponds to a cutting pattern. [37]

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Chritofides and Whitlock published a tree search algorithm in 1977 that has a guillotine-type approach. The rotation of items is prohibited as well. Each node within the tree represents a stage of a rectangle after being cut. The arcs between two nodes embody a cut at a particular position on the rectangle. As a result, the end node of each branch stores a list that contains all cuts to get the final rectangle. The branching is finished when the terminate node consists of only “0-cut” rectangles. A “0-cut” is the final cut to get a rectangle that cannot be cut one more time. The authors describe the effects of symmetry and cut order to decrease the size of the final tree. Forward or backward branching is continued until a branch with the best objective value is found. [43]

Based on Gilmore and Gomory, Suliman published a two-dimensional cutting stock approach in 2006 that seeks a solution to cut a given number of rectangular pieces from a given stock roll with no constraint for the stock length. This method could be applied within the sheet metal industry to cut sheets from a big coil. Cuts are executed from edge to edge, which implicates a guillotine cutting pattern.

The algorithm is divided into three stages. In the first stage, the items’ shapes are aligned in an oriented way onto the stock sheet to receive a width pattern with a minimum width trim loss. Secondly, the width pattern is repeated until a length cutting pattern with a minimum length trim loss is found. As a result, stages one and two create an optimal cutting pattern. In the end, the third stage calculates the number of times the pattern has to be repeated to meet the demand for each item. [48]

Another two-dimensional guillotine type problem without rotation took a different approach and was published by Wang in 1983. Instead of finding and enumerating all possible cuts, cutting patterns are found by adding the demanded items to each other to

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successively build a larger rectangle that fits into the stock sheet. In this way, horizontal builds or vertical builds are imaginable. As rotation is excluded from this method, items are considered as oriented. A horizontal build places the rectangles next to each other to increase the total width. A vertical build places the rectangles on top of each other to add their length together. Hence, this approach is called “reversed guillotine cutting”, as the method is similar to reconnect cut rectangles. As a result, a new rectangle with the size of the smallest rectangle that encloses the two build rectangles is created. Those new rectangles are then added together until the stock sheet size is reached. At any time, the new width or length cannot exceed the stock sheet width or length. By creating a vertical/horizontal stack, a trim loss will appear if the width/length of the two items built together is not equal. The trim loss is used as a constraint to omit all vertical or horizontal builds with a trim loss higher than a previously set bound. Finding the optimal bound is the challenge within Wang’s algorithm as it directly refers to the number of possible patterns and, therefore, significantly influences the computing time. [51]

The vast computational effort leads to an improvement published by Vasko in 1989. Another approach called “Surplus Plate Application Module” (SPAM), published earlier by Vasko et al. [54], is used to calculate an initial upper bound for Wang’s building algorithm. That initial bound leads to a shorter computing time to determine the optimal solution. [45]

In subchapter 2.1.3, common failure modes of solar panels were specified. In this case, a cutting strategy that includes damaged parts within stock objects might be interesting and practical. Such an approach was published by Hahn from IBM Corporation back in 1968. She presented a two-dimensional tactic for rectangular items with guillotine-

type and oriented cutting patterns without rotation. The objective is to minimize the waste and to exclude damaged areas from the stock sheet. The damaged areas are always assumed to have a rectangular shape. Hence, they can be treated as items. A three-stage algorithm is presented to generate cutting patterns. The first stage divides a stock sheet into sections by cutting parallelly to the y-axis. Secondly, the sections are cut into strips by cutting parallelly to the x-axis. In the end, the stripes are further cut into the demanded pieces. For the final optimization, a dynamic programming approach similar to that published by Gilmore and Gomory is implemented. [55]

So far, rotation of items was excluded from all approaches. But the rotation is possible and could also be reasonable in some application cases. Besides, rotation of items could lead to a more optimal solution as areas that otherwise would have been declared as trim loss could be used. In 2020, Cid-Garcia and Rios-Solis presented one of the first exact approaches to solving a rotation problem. It is a two-dimensional bin packing problem (2D BPP), but the primary approach matches the cutting stock problem as mentioned earlier in this chapter. Hence, a 2D BPP algorithm can be well transformed into a cutting stock approach. Nevertheless, there is one fundamental constraint: the algorithm generates non-guillotine cutting patterns. For a potential application case, the cutting machine must be capable of performing non-guillotine cuts. The primary approach is to find the minimum number of two-dimensional bins (larger rectangle), all demanded smaller, rectangular items fit into. It is separated into two stages. In the first place, a positioning algorithm identifies all items' feasible positions within the bin and creates a list of all positions. Secondly, an integer linear programming (ILP) model is computed to find the optimal combination of the items' positions. [52]

Chapter 3

3 Market Overview for Solar Energy and Recycling

Chapter three ties in with the literature review in chapter two and describes the market situation and market development for solar energy and solar module recycling in the New England region. Further, comparisons to other U.S. states are drawn. The last section analyzes second-life approaches found in literature or online articles.

3.1 Solar Energy New England – A Closer Look

Within chapter one – the introduction – brief insights into the solar energy market development in the past and a forecast for the future are presented. Further, Rhode Island is mentioned as playing a pretty important role within the solar energy growth even though it is one of the smallest states within the U.S. This subchapter looks more deeply into Rhode Island's solar energy market development and the development of the remaining New England states. New England is usually referred to as the northeastern region of the U.S. that encompasses Rhode Island, Massachusetts, Connecticut, New Hampshire, Vermont, and Maine.

In January 2020, the Rhode Island Governor – Gina M. Raimondo – issued an executive order to fulfill 100 % of the statewide electricity demand with energy from renewable sources by 2030. [56] That includes not only solar power but onshore and offshore wind, landfill gas, and hydropower. In 2019, Rhode Island's total electricity load was 7,250 GWh, while the previously mentioned renewable energy sources fulfilled 13 % of that demand. [57] Unfortunately, there is no more recent data available.

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In the first quarter of 2020, solar energy was the second largest renewable source with around 300 MW after wind power with 545 MW (onshore + offshore). [58] After six months, the total amount of solar energy grew to 352 MW. The growth is even more impressive when the following data is reviewed: In 2016, the power generated from solar panels was just about 35 MW. [59] That is an increase of about 1000 % in 4 years that can be called highly exponential.

There is an exponential growth in solar energy supply in Rhode Island and many of the United States. Compared to the New England region, which has an increase in solar power from 2016 to 2020 by 218 % in total, Rhode Island can be called as the leader in solar power growth within New England. [60]–[64]

The following table summarizes key facts about solar energy in the New England region.

Table 3-1: New England's Solar Energy Facts [59]–[64]

State	Solar Installed 2019	Solar Installed 2020	Portion of State's Electricity by Solar	National Ranking 2020
Rhode Island	~300 MW	352 MW	5.05 %	25
Massachusetts	~2,740 MW	3,046.7 MW	18.40 %	15
New Hampshire	~111.9 MW	132.9 MW	0.88 %	39
Connecticut	~728 MW	878.6 MW	2.22 %	24
Vermont	~360 MW	379.0 MW	14.03 %	41
Maine	~87 MW	170.7 MW	1.14 %	29

The national ranking is based on the installed capacity in 2020 and, therefore, highly depends on whether a state has started to ramp up its solar energy capacities more recently or not. Maine, for instance, almost doubled its solar energy capacity in the last year, while

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Vermont only added a few MW. Nevertheless, Vermont has the second-highest solar energy portion of its state electricity demand. Another example is Massachusetts, where solar energy is a proper contributor to the state's electricity generation.

In comparison to the data from New England, the following table shows the solar energy facts of the states being on rank one, two, and three in the United States. All three states are among the biggest electricity consumers in the country and probably among the sunniest states in the United States.

Table 3-2: Solar Energy Facts of Ranks 1,2 and 3 [65]–[67]

State	Solar Installed 2019	Solar Installed 2020	Portion of State's Electricity by Solar	National Ranking 2020
California	~27300 MW	31,288.0 MW	22.69 %	1
Texas	~3320 MW	7,784.6 MW	1.97 %	2
Florida	~3600 MW	6,539.8 MW	3.03 %	3

California is by far the leader of the total solar energy installed and the annual installation rate in 2020. Further, they have the highest portion of solar energy in the state's electricity mix. Concerning the growth rate in percent, Texas and Florida almost doubled their solar capacity in the last year. If the growth continues, their portion of solar energy in the state's electricity mix will be significantly higher in a few years. [65]–[67]

In conclusion, solar power growth is enormous and indicates a high trust in solar energy as a sustainable fuel type for society.

3.2 Recycling and Regulations

Section 3.2 firstly describes the recycling structure in Rhode Island. As the Rhode Island region is the study's primary focus, this section goes more into detail than the succeeding sections. Next, a brief overview of current regulations and activities regarding solar module recycling in the New England states is presented. Finally, section 3.2.3 gives a short introduction to what the leading states in solar module recycling are doing and names important solar module recycling companies within the U.S. market.

3.2.1 Recycling Structure Rhode Island

On the one hand, a recycling structure in Rhode Island does exist, and on the other hand, it does not. The reasons for that are missing regulations for the recycling of solar panels in Rhode Island. Even though there is a so-called “Electronic Waste Prevention, Reuse and Recycling Act” [68], e-waste from solar panels is not part of that proclamation. The “Electronic Waste Prevention, Reuse and Recycling Act” mainly applies to electronic consumer goods like computers, monitors, and TVs. [68]

However, the case of missing regulations applies to Rhode Island and most of the United States. [34] As a result, in Rhode Island, solar panels are declared as regular solid waste, and local landfill disposal is not prohibited. Additionally, landfill disposal is also much cheaper than the recycling fee for the more or less existing recycling structure for solar panels in Rhode Island. According to the RIRRC fee schedule from 2021, the rate for non-contract solid waste for commercial and residential purposes is \$115 per ton. In contrast, RIRRC charges \$1350 per ton for the acceptance of solar panels with recycling intention. [69] Hence, solar panel disposal for recycling purposes is almost twelve times more expensive than sending them into landfills. That might be the apparent reason why

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RIRRC only received three solar panels for recycling in the past three years, according to an e-mail exchange with the RIRRC outreach manager Madison Burke [70] and a short interview with Mike Doran from RMG [71].

RMG is mainly an e-waste recycling company for e-waste that is embraced by the “Electronic Waste Prevention, Reuse and Recycling Act” like computers and so on. They primarily have focused on the on-site recycling of CRT TVs. However, they partner with RIRRC for solar panel recycling. According to a telephone call with RMG’s business development manager Mike Doran, they have no on-site competence to recycle solar panels. [71] They are sending the panels to Cascade Eco Materials, a glass recycling company located in Ohio, which recently started recycling solar panels. They advertise a close to 100 % recycling of solar panels on their website but do not offer more detailed information on their processes. [72]

3.2.2 Recycling Structure New England

This subsection will provide a brief overview of current recycling approaches, activities, and programs in the New England states and whether there are some activities concerning that topic at all.

Massachusetts

The Massachusetts Department of Environmental Protection (MassDEP) is responsible for all activities and law enforcement dealing with the air, land, and water protection in Massachusetts. Hence, MassDEP is also responsible for all waste regulations. [73] So far, Massachusetts does not have any recycling requirement for solar panels.

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Nevertheless, the state's solid waste regulations for landfill disposal require a test for hazardous materials. Hence, solar panels have to be tested and are banned from landfill disposal if hazardous materials are present, as some solar panel types are considered hazardous. Further, the MassDEP published a guideline with several questions and answers regarding ground-mounted solar systems. That guideline includes a short end-of-life section that mainly says something about the expecting lifetime of solar panels and the required testing whether the particular solar panels contain hazardous materials or not. The testing could be either done through a material list provided by the manufacturer or by specific test procedures. [74]

Besides, the guideline encourages solar projects to include an end-of-life management plan in their project proposals. Finally, the guideline provides a brief description of companies and organizations starting to recycle solar panels. [74]

Furthermore, the MassDEP has set up a technical assistance program to advise local companies on recycling and disposal questions. A searchable database called "Find-a-Recycler" can be used to find the regulations and organizations dealing with certain services. That program refers to several smaller recycling companies like "Good Point Recycling" [75], "EarthWorm Recycling" [76], and "Complete Recycling Solutions LLC" [77]. These companies are mainly traditional e-waste recyclers trying to ramp up solar panel recycling capabilities and capacities. So far, most of them are warehousing the panels until a proper solution is found.

Maine

The governmental organization for waste management in Maine is similar to Massachusetts and is called the "Maine Department of Environmental Protection" (Maine

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DEP). However, Maine does not have any recycling programs or policies for solar energy waste management so far. [78] Nevertheless, some effort was made to propose a regulation to implement a consumer-funded recycling program. [79] But the outcome is not clear yet. Further, the proposal is likely to fail, as Megan Mansfield Pryor, environmental specialist at the Division of Materials Management at Maine Department of Environmental Protection, stated in an email.

Furthermore, the Main DEP annually publishes a product stewardship report to address the need for product stewardships for certain identified products. Solar panels are listed within that report since 2019 to emphasize the need for special end-of-life programs for solar energy systems. [80]

Vermont

In Vermont, the Agency of Natural Resources runs the Department of Environmental Conservation (VT ANR-DEC). The division “Waste Management & Prevention Division, Solid Waste Program” is responsible for all waste management programs. So far, there is not any program available for the proper recycling of e-waste from solar systems. Further, the VT ANR-DEC currently does not see a strong regional market for solar panel recycling. [81] That is interesting, as Vermont has the highest portion of solar energy among their state electricity mix after Massachusetts (see table 3-1).

Nevertheless, the VT ANR-DEC is watching current solar panel waste management developments and emerging programs or product stewardships in other states. One ideal is Washington state, as Josh Kelly, materials management section chief within the waste management division, stated in an e-mail.

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Furthermore, Vermont is cooperating with Good Point Recycling, mentioned above, as a partner for traditional e-waste recycling. As they are also working together with the MassDEP, there may be future cooperation between New England states concerning solar panel recycling.

New Hampshire

The New Hampshire Department of Environmental Services (NHDES) combines all water, air, land protection, and waste management services. So far, there are no regulations available concerning the recycling of solar panels. Like all other recently mentioned state's waste management divisions, the NHDES also distinguish between hazardous and solid waste. However, no guidelines are available on their website to determine whether solar panels would be considered hazardous or solid waste. [82]

Nevertheless, New Hampshire and Vermont enacted a law that requires solar farm operators to provide a decommissioning plan for solar panels at their end-of-life. However, the regulation only applies for solar farms above 30 KW or 1 MW, respectively, and does not dictate recycling. [83]

Connecticut

The waste-responsible department in Connecticut is the Department of Energy and Environmental Protection (DEEP). Like the other New England states described above, Connecticut does not have any program for solar module recycling. [84] Nevertheless, recently, Connecticut convened a stakeholder engagement process called "Sustainable, Transparent and Efficient Practices for Solar Development". The objective is to identify policies, legislative actions, and best practices concerning solar energy systems.

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Unfortunately, a proper end-of-life management for solar panels seems not to be included in that program as there is no information available. [85]

3.2.3 Organizations and Regulations – USA

The biggest reason for the cross-state lack of regulations, programs, and guidelines for the proper handling of end-of-life solar modules most likely lay within U.S. federal leadership and missing federal laws. Hence, every state is on its own. Most of the states are, at least, observing the solar energy recycling market but have not enacted any regulations so far. However, as mentioned above, some states like Washington, California, Arizona, and others have made some steps in the right direction. [34]

Washington state is ahead of all other states and enacted stewardship and take-back programs that will come into force on January 1st, 2021. [86] It will force all solar module suppliers to provide a recycling plan for solar energy projects. [34] As large-scale, so-called utility-scale solar farms initially had been excluded from the program, in April 2020, another Washington House Bill was signed that expands the program to include utility-scale solar farms. [86]

On the other hand, California is the only state that classifies e-waste from solar modules as universal waste and established guidelines for solar energy waste treatment and disposal. [83] As a result, treatment procedures are regulated, and recyclers must be authorized for waste treatment and processing. However, proper recycling is not ensured as the definition for solar module does not apply after the solar module has been taken apart in its parts like the aluminum frame, the conjunction box, and the remaining material sandwich shredded into tiny pieces. [87]

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Furthermore, Arizona took significant steps towards solar module recycling when introducing a landfill ban for solar modules and electric vehicle batteries in February 2020. Additionally, a \$5 fee per solar module for manufacturers applies if they do not implement a sufficient recycling program. [88]

Besides state government activities, several associations are dealing with the end-of-life management of solar panels.

The Solar Energy Industries Association (SEIA) is the national trade association for solar energy to combine research, education, and advocacy for everything around solar energy. [89] SEIA runs a federal PV recycling program that consults its members concerning proper end-of-life solutions. Also, SEIA brings together manufacturers, vendors, and recyclers to ensure cost-effective and environmentally friendly end-of-life opportunities. Further, many SEIA members have already implemented product stewardships or take-back programs. However, it is not required to become an SEIA member. [90]

Another agency dealing with end-of-life and waste management solutions for solar modules is the European-based PV Cycle. On the one hand, PV Cycle offers different memberships for solar energy companies. On the other hand, PV Cycle provides take-back and recycling services for solar systems, including solar modules, inverters, and batteries. [91] Further, they cooperate with companies like “Recycle PV Solar” to establish proper recycling in the United States. [92]

Focusing on the northeast part of the U.S., the Northeast Recycling Council (NERC) is essential to mention. NERC is a non-profit organization founded 33 years ago and includes eleven states: Connecticut, Delaware, Maine, Massachusetts, New Hampshire,

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New Jersey, New York, Maryland, Pennsylvania, Rhode Island, and Vermont. While NERC develops projects that influence and change policy, other programs are introduced to emphasize reuse and recycling in general. [93] Further, NERC has acquired several members from substantial global players like The Coca Cola Company, Panasonic, or Samsung to local recycling companies like Good Point Recycling [75], mentioned earlier. [94] NERC is also discussing concerns about solar panels' end-of-life management. [93]

Apart from non-profit agencies or associations, some companies are starting to ramp up recycling facilities in the United States. Cascade Eco Materials, mentioned in section 3.2.1, is one of those companies. Another company is called We Recycle Solar [95]. We Recycle Solar established facilities at ten locations in four different countries like the USA, Japan, Belgium, and South Korea. [86] According to their website, each site can recycle 100.000 pounds of solar energy equipment per day. [96] That amount equals 45,4 metric tons and includes all components of a solar energy system [96]. Hence, the realistic amount of recycled solar panels is not given.

3.3 Second-Life

Discarded solar panels, in most cases, are still working even if the glass is shattered and the panel's appearance indicates a terrible condition at first sight [97]. That fact is also proved in chapter four. However, the break-even calculation in chapter four shows that technical malfunction is not the only reason for disposal. Instead, repowering solar farms will be a massive contributor to the volume of discarded solar panels that will still be in good condition.

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Within the introduction of this study, some potential second-life use cases have already been mentioned. This subchapter provides more details on various imaginable second-life approaches and gives a clustering example.

3.3.1 Potential Use Cases

There are several second-life approaches for used solar panels imaginable. Within this study, second-life approaches are clustered into two different main sections: remanufacturing and repurposing. The main difference between both cases is the cutting into individual rectangular sizes. Repurposing does include the cutting of solar panels, and remanufacturing does not.

For the remanufacturing case, the solar panels should be tested, in the first place, whether the remaining performance is still reasonable. Afterward, the solar panel could be resealed if the panel glass has been damaged and sold as used solar panels. A market for those used solar panels exists for cheap off-grid solar systems or as support for fragile and small grids in countries like, for example, Mexico [97]. Further, second-life panels serve as an affordable opportunity for developing countries to increase their green electricity share. Those secondary solar markets significantly increased in 2020 in the Middle East, Africa, Latin America, and the Caribbean. [4]

According to the report “Energy projections for African countries” published by the European Commission in 2019, a significant share of electrical energy in Africa is produced by diesel-powered generators [98]. When remanufactured with limited costs, reused solar panels could serve as bridge-solution to reduce diesel-generated electricity at least during the day. Those systems could be linked to second-life battery storage systems as soon as higher amounts of used car batteries enter the second-life market. As a result,

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renewable off-grid systems based on second-life equipment could be assembled and provided. However, the challenge is to keep the remanufacturing costs as low as possible, which might only be feasible with large-scale processing but has to be further investigated.

The second case mentioned above is the repurposing of used solar panels to extend their lifetime. The repurposing, in this context, includes the cutting of solar panels into individual sizes to increase the range of thinkable applications. The reshaping is needed to create solar panels with individual voltage and power levels. Further, the resulting low-power panels have a smaller size and thus are much more flexible concerning their application and installation. The smaller size makes it possible to use second-life solar panels for RV projects, for instance, as they can be easily installed on RV's rooftop. Standard-sized solar panels would be simply too huge.

Another application case, even though battery storage would be needed, is the off-grid powering of communication systems or other infrastructures like 5G or streetlights. Those systems need only little energy and therefore could be powered by repurposed solar panels of smaller sizes. [6] Even the indoor application of solar systems is imaginable as the Internet of Things (IoT) is gaining in popularity. [99] The indoor application of resized second-life solar panels would be even easier and cheaper, as resealing the potentially damaged front glass would not be necessary.

Moreover, an interesting recent development is the direct integration of solar cells in tiles. Even though every tile just generates a power output of around 10 W, the whole rooftop area will add up to the capacity to almost power the household. [100] The primary advantage is the direct integration of solar cells into the roof surface. Hence, no additional mounting structure is necessary. From a second-life perspective, those tiles could also be

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equipped with repurposed solar cells from standard-sized solar modules cut into demanded sizes.

Another example for the repurposing of standard-sized solar panels is the application in an off-grid power station. The solar panels combined with a second-life battery could provide renewable energy from second-life equipment to charge mobile devices like smartphones, tablets, or laptops. That approach is the central use case chosen for this study. In the following chapter four, the creation of a prototype for such a system is reported.

However, for each imaginable use case, a profitability analysis would be necessary to prove the feasibility of a business purpose. Nevertheless, for the collection of used solar modules, a fee can be charged that will help to keep the cost for second-life products as low as possible.

3.3.2 Regulations

In either way, whether remanufactured or repurposed, there might be regulations for the treatment and reselling of second-life solar modules that depend on the state laws. In California, for instance, companies have to be authorized to treat solar energy waste. [87] However, such rules mainly apply for the recycling purpose of used solar panels. It is hard to find what kind of regulations are relevant for the U.S. secondary solar market.

One of the most significant issues for the reselling of used solar panels is the warranty. In most cases, the initial warranty provided by the manufacturer is non-transferable. [4] Hence, a secondary use would cause the solar panels to lose their warranty even if they have not reached the 25 years of typically warrantied lifetime. Some secondary markets in areas with above-average sunlight irradiance like Afghanistan, Pakistan, Somalia, and other African countries do not care about the missing warranty or possibly

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lower efficiency of used solar panels. Instead, lower prices for solar panels enable them to push forward their renewable energy sector. [4]

The first solar equipment reseller companies have started counteracting missing warranties by testing all incoming solar panels and providing a limited warranty at their own risk. That helps to break doubts customers might have while considering buying used solar panels. [4]

Chapter 4

4 Second-life Approach for Solar Panels

Chapter four is one of the two central chapters within this study. This chapter deals with the second-life approach for solar panels and the motivation to consider a second-life within their life-cycle. Further, experiments and investigations conducted in one of the University of Rhode Island (URI) engineering labs shall demonstrate the possibility to remanufacture and repurpose solar panels.

Several challenges had to be overcome to complete the empirical work related to the reuse of solar panels. The first main challenge was to obtain some used solar panels for the investigations as buying new ones would not have made much sense for this study because new panels would not have been exposed to the normal operational wear, and furthermore, would have added to the costs for experiments. Generously, Rhode Island Resource Recovery Corporation (RIRRC) made a great effort to find three solar panels still sitting within the recycling chain described in chapter three. Those panels were delivered to the URI engineering lab and used for the experiments described in the following subchapters.

The first subchapter describes the general approach and explains the proposed process chain as there are several opportunities and cases imaginable. Secondly, the two significant motivating factors for extending the lifetime of solar panels with a second-life approach are stated. Afterward, the experimental part of the study is described, and challenges for the experiments are illustrated.

4.1 The General Approach

The central motivation of this study is to extend a solar panel's lifetime by enabling a second life. Various second-life approaches are possible and have already been mentioned in chapter three. Within this study, two cases are possible: the first case is when the tempered glass coating on the incoming panels is shattered, and the second is when it is intact. A general process for both cases is shown in Figure 4.1.

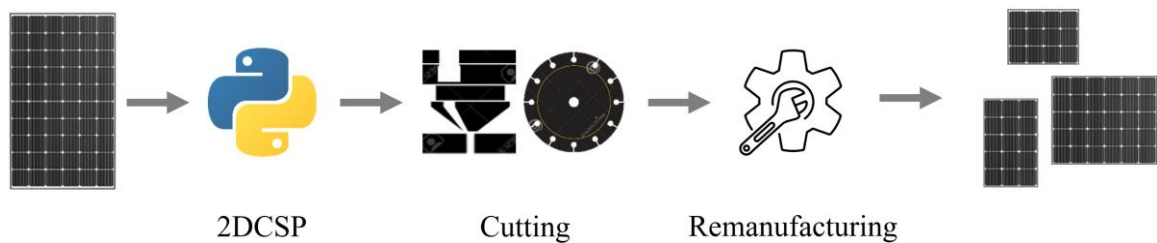


Figure 4-1: Primary Second-Life Approach

The end result of this process is to subdivide standard sized panels into smaller ones in three main stages. Stage one, the two-dimensional cutting stock problem (2DCSP), tries to develop a suitable cutting stock approach to find the best cutting strategy in the case of solar panels. This part is reported in chapter five. The “Cutting” stage applies an appropriate cutting method to reshape the panels. As the optimal cutting technology has to be found, experiments are conducted in subchapter 4.3. After the solar panels are cut, a remanufacturing process is needed that reconnects the silicon cells in the smaller panels and remanufacture the frame and sealing.

As mentioned above, the front glass’ condition is crucial for the whole process. The significant differences are summarized in the table below.

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Table 4-1: Influence of Sound or Shattered Glass on the Process

		Stage		
		Cutting	2DCSP	Remanufacturing
Type	Panel with intact glass	Appropriate cutting technology is needed to cut tempered glass successfully	It depends on cutting technology	A new aluminum frame has to be supplied
	Panel with shattered glass	The shattered glass enables the use of abrasive cutting technology like a diamond cutting blade	It depends on cutting technology	In addition to a new frame, the whole panel surface has to be sealed to restore the encapsulation

The tempered glass's condition does not have any influence on the programming of the cutting stock approach. In either case, it depends on the cutting technology, as chapter five will reveal. But the “Cutting” and “Remanufacturing” stage is influenced by the condition of the glass. A broken front glass mainly simplifies the cutting itself, as described in the table. However, it complicates the remanufacturing as an aluminum frame has to be supplied, and the surface area has to be resealed.

4.2 Supporting Facts for a Second-Life Approach

There are several supporting facts for extending the solar panels' lifetime, and at least one or two of them have already been mentioned in the previous chapters. On the one hand, chapter one cited an article in the PV Magazine [34] that talked about fully-functioning solar panels that probably end up in U.S. landfills. On the other hand, chapter two mentioned a study showing that even 40-years old solar panels produce a sufficient amount of electricity far above 90 % of their original efficiency [24].

The efficiency of solar panels is an essential factor when considering the replacement of solar panels on rooftops and commercial utility-scale systems. That is because installed

Chapter 4 - Second-life Approach for Solar Panels

panels experience an efficiency degradation while new panels become more powerful and more efficient due to innovation and technology enhancements (see chapter two). Hence, at some point, it economically makes sense to replace the panels. A calculation for this is shown in subchapter 4.2.2.

Beforehand, section 4.2.1 picks up the solar panel's life cycle assessment (LCA) again and explains the advantage a second-life approach can have.

4.2.1 Embodied Energy / LCA

Subchapter 2.1.5 describes the LCA approach and the significance of the solar panels' embodied energy for the energy payback time (EPBT), which is a decent indicator of their sustainability. The review paper [31] published by Gerbinet et al. in 2014 summarizes various LCAs that have been conducted in different countries for different types of solar panels. The average EPBT is about two to four years but varies between 1.45 [101] and 7.4 years [102]. So, the solar panel can re-pay their embodied energy with very little use. But that is certainly not the point. One of the key arguments for solar panels' sustainability is the ability to pay back their embodied energy many times within the warranted lifetime of 25 years. If the panels are disposed of earlier, the vast potential of producing green energy is not entirely used to total capacity. A second-life approach would extend the panels' possibilities to produce green energy beyond that point where just the embodied energy has been paid back.

Besides the EPBT, the global warming potential (GWP) was mentioned within subchapter 2.1.5. As environmental discussions today are mainly about reducing CO₂ emissions drastically, having a look at those emissions is worth it. The study cited in chapter two calculates the GWP for PV panels in kgCO₂-equivalents per kWh, a standard

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unit within LCAs. It was conducted in China, where coal-fired power plants generate most electrical energy. Even though the electricity used to manufacture the PV panels is not green, the results show that the GWP of PV panels is much lower than electricity coming from non-renewables. The results show a GWP for the particular PV panels of 0.05 kgCO₂-equivalents per kWh [35]. Even with the non-renewable energy used for manufacturing mentioned above, the results match other LCAs that show a range of 0.012 to 0.170 kgCO₂-equivalents per kWh [103]. But the GWP is calculated per kWh electricity produced by the solar panels in an assumed operation time of 25 years [35]. Reducing the time of operation by replacing solar panels early, the greenhouse gas emissions per kWh electricity produced by PV panels increase dramatically. Hence, extending the lifetime of PV panels as long as possible and at least up to their warranted lifespan of 25 years is crucial, especially for solar panels produced with non-renewable energy. As most PV panels are made in China with coal-fired energy, the lifespan is a crucial aspect of PV power sustainability.

4.2.2 Break-Even Analysis for the Replacement of PV Systems

The estimated volume of e-waste from solar panels is another crucial aspect that is always based on the technical lifetime of 25 or 30 years. One example is the End-of-life Management Report published by the International Renewable Energy Agency (IRENA) in 2016. The report states, among others, the solar panels' e-waste predictions until 2050, as figure 4-2 shows [2]. Even though a regular-loss scenario and an early-loss scenario have been calculated, the predicted amounts might be underestimated. Both scenarios assume a technical lifetime for solar panels of 30 years and a 99.99 % probability of loss after 40 years.

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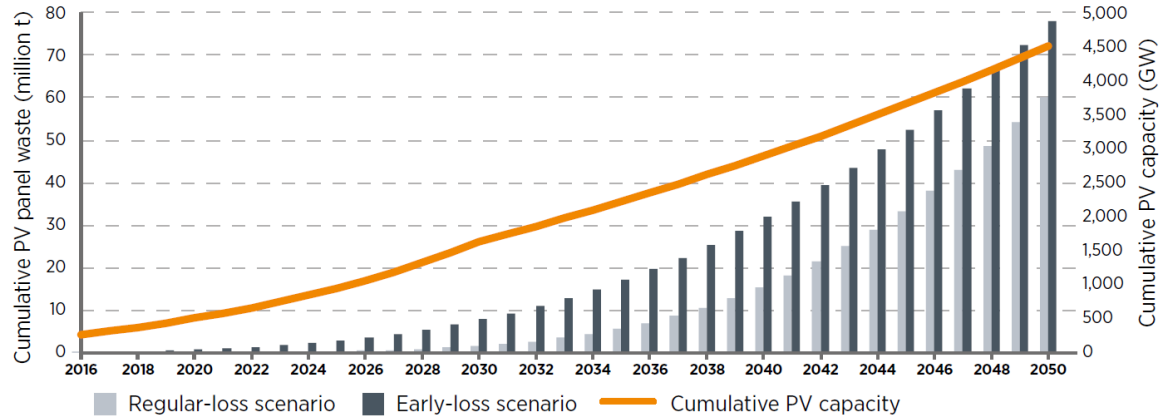


Figure 4-2: IRENA – Prediction for E-Waste from Solar Panels [2]

First of all, a study shows that even up to 40 years old panels can still generate electricity, although the conversion efficiency drops considerably [24]. Hence, the basic assumption of nearly 100 % loss not later than after 40 years might not be generally correct.

However, the essential and debatable fact is that the lifetime assumption in both scenarios is only based on loss due to technical malfunction. Even the early-loss scenario only considers a higher technical failure probability during the initial years. With specific failure rates, a Weibull distribution, which is a standard model to predict the lifetime of technical devices, was created to model the lifetime distribution of solar panels. [2] Thus, the e-waste prediction totally disregards the replacement of solar panels due to other reasons than technical failure.

One possible reason was already mentioned in introducing subchapter 4.2 and is about the replacement due to economic reasons. This aspect is also mentioned in recent articles [34] and was described in chapter 2.1.3.

In this thesis, a spreadsheet model was developed to emphasize the economic factor as a significant contributor to solar panel replacement and e-waste generation. The goal is

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to find the year t where the replacement of the PV modules might be economically efficient. There are several input data and facts necessary for the modeling described in the following paragraphs.

The Efficiency

The efficiency of a solar panel is defined as the rate of 1000 kWh sunlight per year per square meter that can be transformed into electrical energy [18] as 1000 W/m² solar irradiance for 2.74 h/day is the standard test condition [104]. Hence, a PV module with 20 % efficiency generates 200 kWh electrical energy per year per square meter. The efficiency is usually referred to as the conversion efficiency η . However, at a given point in time, panels of different efficiencies can be purchased, with a premium for higher prevailing efficiencies. For example, in 2015, panel efficiencies ranged between 15 % and 17 % for multi- and mono-crystalline silicon solar panels, and currently, this range is 18 % and 21 % (see section 2.1.1). However, the efficiency highly varies whether laboratory or in-field test conditions are chosen and what type of solar panel is considered.

Another major factor in the replacement of installed panels is the degradation over time (d), that can be between 0.5 % and 3 % per annum (see chapter 2.1.3). The panel efficiency at time t can then be calculated as:

$$\eta_t = \eta_{t-1} * (1 - d) \quad (1)$$

Here η_t is the actual efficiency at time t , and $\eta_{t=0} = \eta_i$ the initial efficiency at the time of purchase.

As mentioned above, continuous improvements in solar cell technology and innovations in manufacturing processes have led to steadily increasing efficiencies of PV

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modules. Figures 2-1 and 2-2 in subchapter 2.1.1 show that the growth can be assumed as linear with a growth rate of 0.5 to 0.7 percentage points per year. Those facts lead to a significant efficiency gap that grows over time, as the following figure shows.

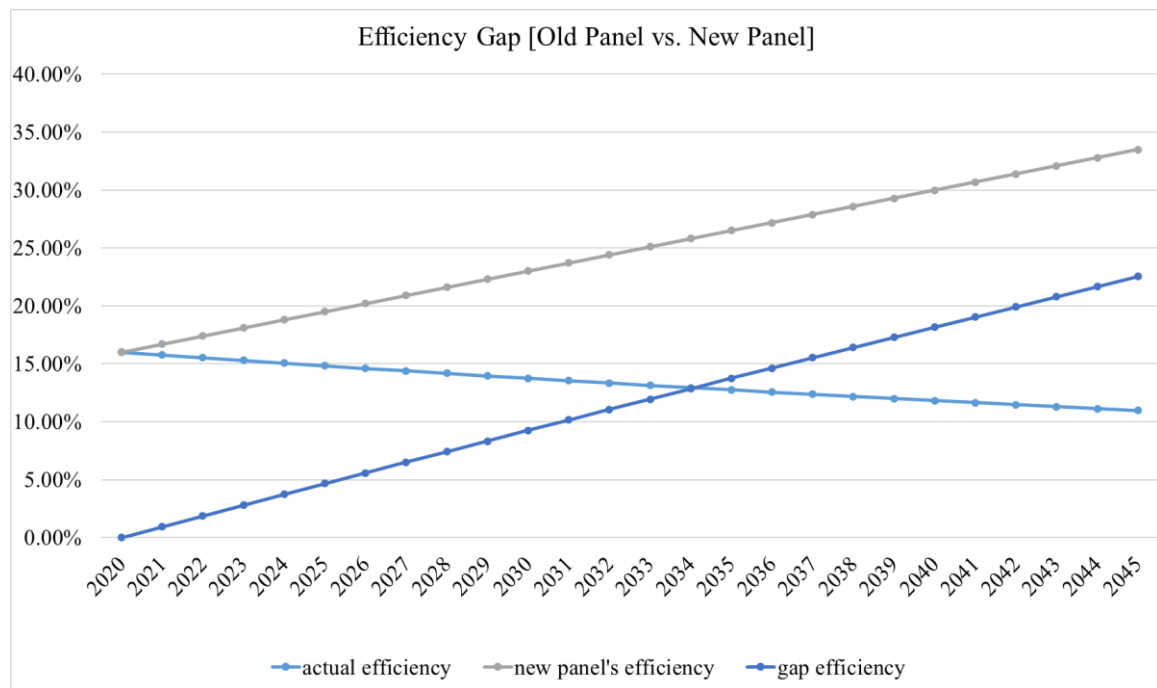


Figure 4-3: Efficiency Degradation and Efficiency Gap to New Panels

In this graph, the efficiency degradation is set to 1.5 % per year, and the efficiency increase of new panels is 0.7 percentage points per year.

Price Development

Prices for solar panels and electricity are continuously changing. The actual residential price for electricity in Rhode Island was 24.09 cents per kWh in February 2021, referring to the monthly report from the U.S. Energy Information Administration (EIA). [105] Historical data from 1999 to 2018 show an average annual increase of 3.8 % in the industrial and commercial sectors [106]. As similar statistics are not available for the residential sector, the growth rate within the residential sector is assumed to be the same.

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Besides, the electricity price highly varies within the United States. The New England states, California, and New York have the highest prices (above 0.20 cents). [105]

Prices for PV modules are compared in \$ per watts and highly vary based on the following factors:

- installation in the residential or non-residential sector
- the scale of the system
- type of PV technology (poly-crystalline, mono-crystalline, other)
- Utility with sunlight tracking or without sunlight tracking
- what costs are included in the price in \$ per watt

Especially the last factor is essential as the solar panel itself only contributes to almost half of the price. The other half splits on costs for PV inverter, electrical and structural balance of system (BOS), direct labor for installation, design and engineering, and the supply chain, overhead and margin. [8] Further, the particular sector and the scale factor also significantly influence the costs (see figure 4-4).

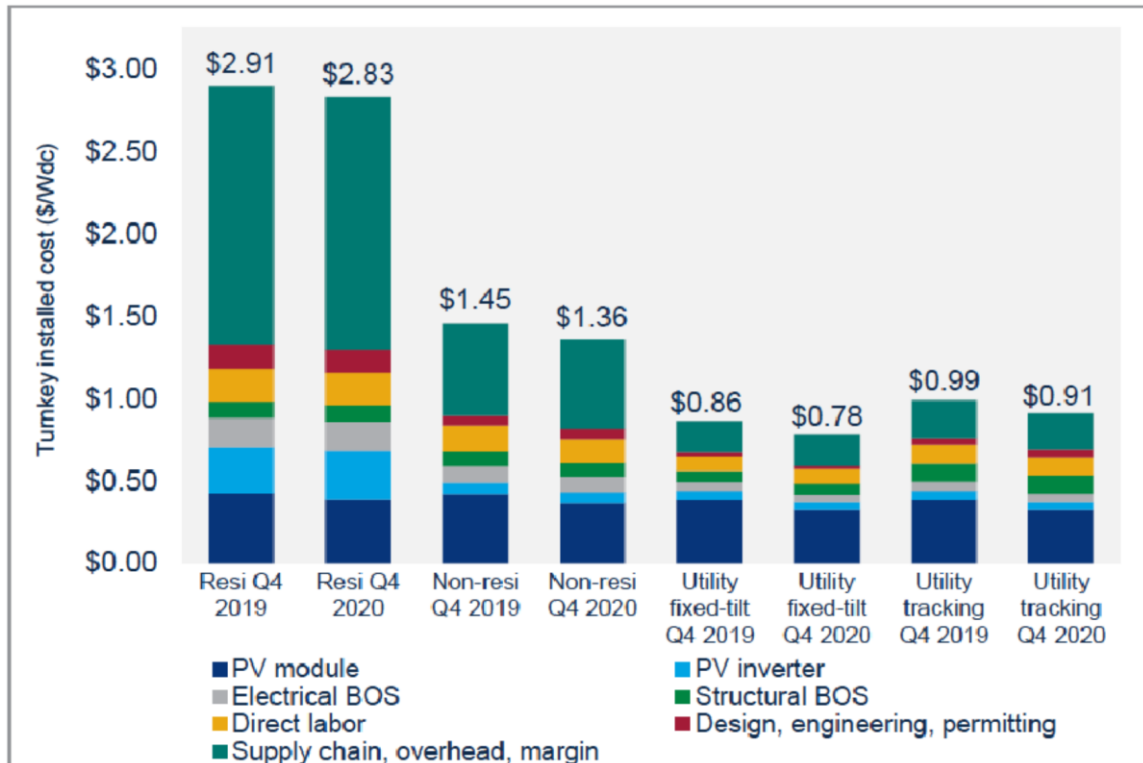


Figure 4-4: Price Composition of PV Systems in Different Sectors [8]

Figure 4-4 also shows that utility-scale PV systems with fixed tilt have the lowest price. Further, prices for all systems decreased by almost ten cents in one year, mainly due to decreasing prices for the PV modules themselves. Other sources like the utility-scale solar report by Berkeley Lab show quite similar price declines. [107]

Within the spreadsheet calculation, a more conservative decrease rate of 3% per year is assumed. The resulting graph for the electricity price and the price per watt of the solar system is shown in the following figure. The initial price for new panels is set to \$0.70 and includes every part of the costs described above but the structural and electrical BOS. It is assumed that those parts can be reused.

Figure 4-5 summarizes both price developments.

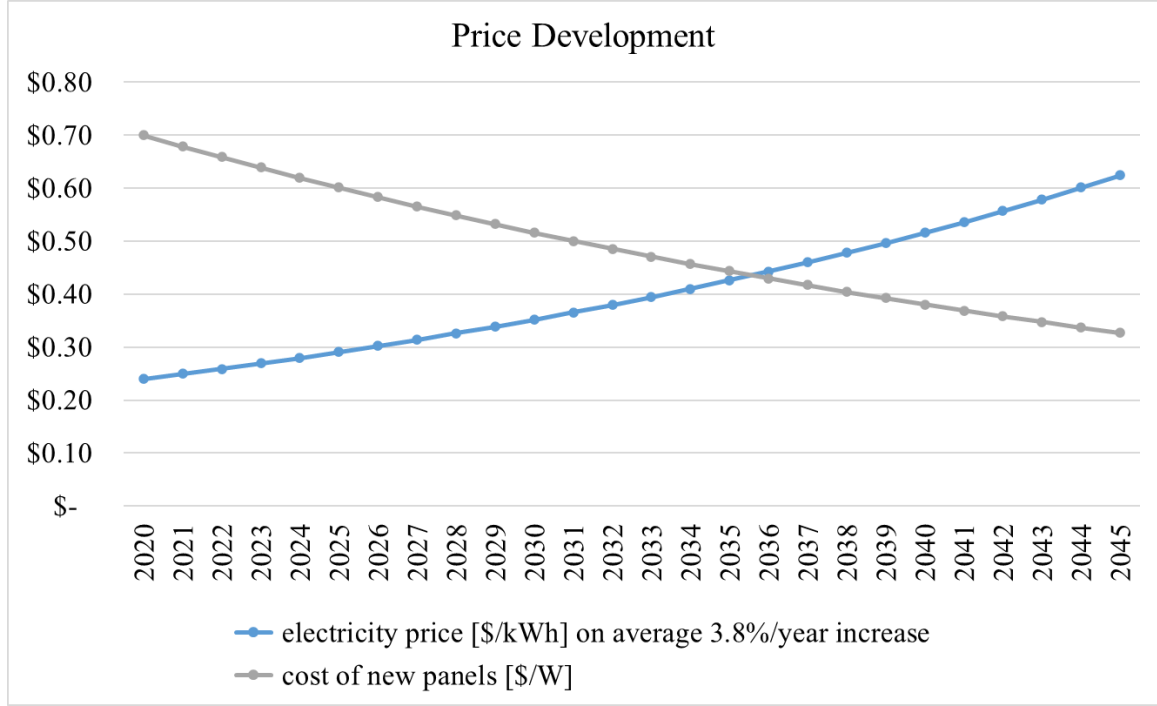


Figure 4-5: Price Development

Excess Revenue

Finally, the replacement costs have to be opposed to the potential excess revenue that could be generated if a replacement with more efficient PV modules has been made. Therefore, first of all, a comparable unit has to be found.

The PV modules efficiency η is the rate of 1000 kWh sunlight per year per square meter that can be transformed into electrical energy as described above. As a result, the comparable unit for the replacements costs and the excess revenue is dollar per square meter.

The excess revenue E in \$/year/m² is calculated as follows:

$$E = (\eta_c - \eta_t) * 1000 \frac{h}{year} * \pi_t \quad (2)$$

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Here η_c is the new panel's efficiency, η_t the actual panel's efficiency in period t , and π_t the actual price per kWh in period t .

Replacement Costs

To calculate the replacement costs R in $\$/m^2$ for a solar system, two particular variables are necessary – the new panels' costs c including all relevant portions of costs in $\$/W$ and their efficiency η_c .

$$R = c * 1000 \frac{W}{kW} * \eta_c \quad (3)$$

While comparing the costs for a potential replacement of solar panels, it is substantial to consider subsidies as there are still significant subsidies on PV systems.

Subsidies

The U.S. enacted its federal Investment Tax Credit (ITC) program in 2006 and has boosted the solar industry by 10,000% since then. It is a 26% tax credit that applies to residential, commercial, and utility-scale solar farms and reduces the federal income tax by 26% of the solar system costs [108]. Besides, at least two other subsidies are available: the state tax credit that is quite similar to the ITC but varies between states, and the Modified Accelerated Cost Recovery System (MACRS) [109]. The MACRS is a method that allows accelerating the depreciation for tax purposes on specific properties. Within the MACRS, solar systems like other renewable technologies qualify for a five-year cost recovery period. [110]

The ITC program is supposed to decline to 22% in 2023 and will settle at 10% in 2024. But as other tax credit programs will remain, the consideration of subsidies for the

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replacement cost of solar panels is reasonable. Therefore, for the spreadsheet calculation, constant subsidies of 26% are assumed. As the future subsidies are difficult to forecast, the final results are presented for the case with and without subsidies.

Results

Table 4-2 sums up all initial input data for the spreadsheet calculation that has been described in the previous paragraphs.

Table 4-2: Initial Input Data for Spreadsheet Calculation

Description	Value
Initial efficiency	16 %
Efficiency increase	0.7 %-points/year
Efficiency degradation	1.5 %/year
Initial costs of new panels	\$ 0.70 /watt
Decline of costs for replacement	3 %/year
Initial price per kWh	\$ 0.24
Increase of electricity price	3.8 %/year
Assumed subsidies	26 %

The spreadsheet shown in appendix 7.1 shows all relevant values calculated for periods 0 to 25 years. From the spreadsheet shown in appendix 7.1, several graphs can be created.

First of all, figure 4-6 shows the replacement cost with and without subsidies and the excess revenue a potential replacement would generate in a particular year. Further, the cumulative excess revenue is shown.

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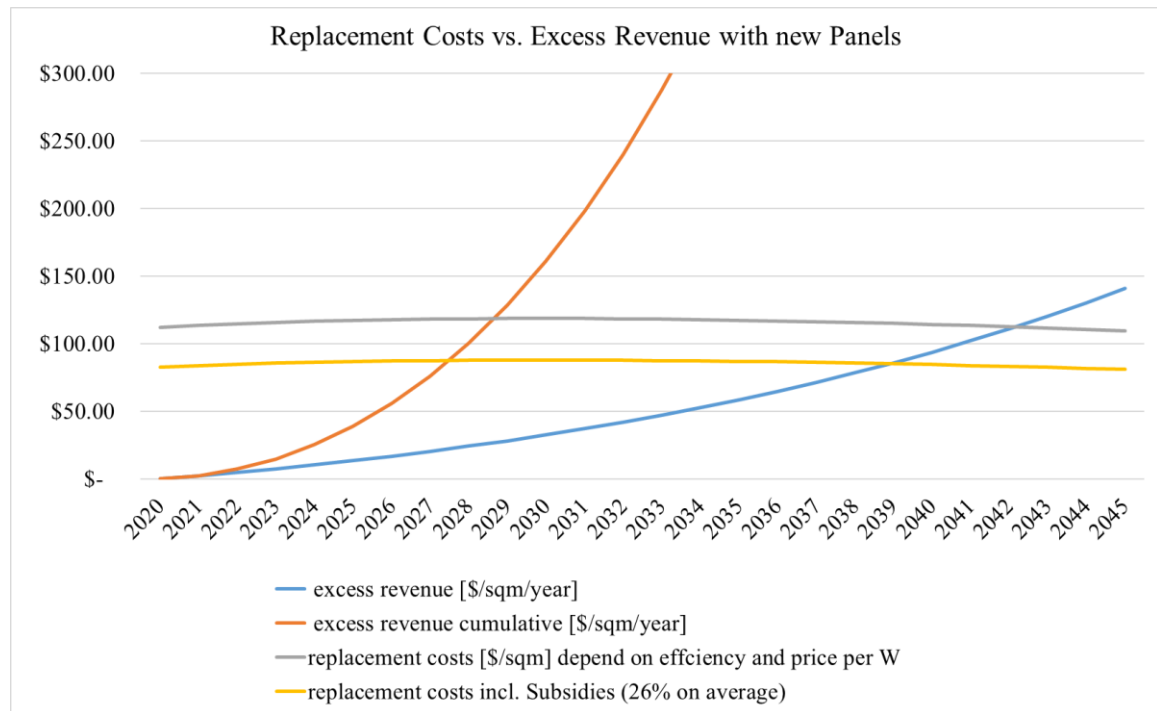


Figure 4-6: Replacement Costs vs. Excess Revenue with New Panels per Period t

The replacement costs have a slightly curved trend as the efficiency of new panels goes up while the price per watt decreases over time. However, the most significant finding from this particular graph is that the excess revenue per year (light blue curve) outperforms the replacement costs with subsidies in year 19 and without subsidies in year 22. Hence, a replacement without subsidies (with subsidies) in year 22 (19) would pay itself in just one year.

An investment usually does not have to pay off within a single year. Especially the MACRS, mentioned previously, qualifies solar systems for a cost recovery period of five years. Hence, the number of years a replacement within a certain year would need to pay for itself was calculated. Again, the case with subsidies and without subsidies was considered.

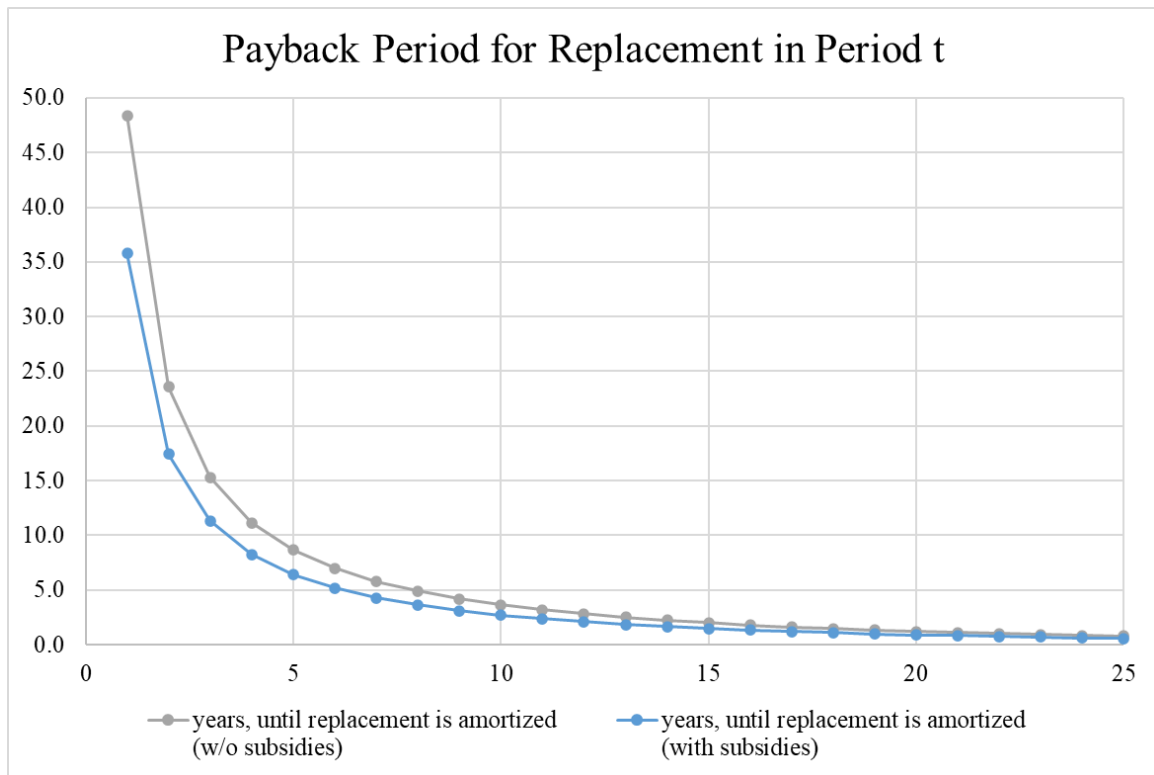


Figure 4-7: Payback Period for Replacement in Period t

Firstly, figure 4-7 shows the payback period a replacement in a particular year would have. The grey curve illustrates the case without subsidies, and the light blue curve the case with subsidies. A replacement within the first years would take many years to amortize as the efficiency gap is too small between the old installed panels and the newer, more efficient ones. But already, after five years, the payback period drops to lower than ten years. Just three years later, the replacement would pay for itself after five years which matches the method of the MACRS.

The efficiency gap is the most significant factor influencing the replacement period. Hence, a similar figure was created that shows the efficiency gap in percent on the x-axis. This graph is shown in figure 4-8.

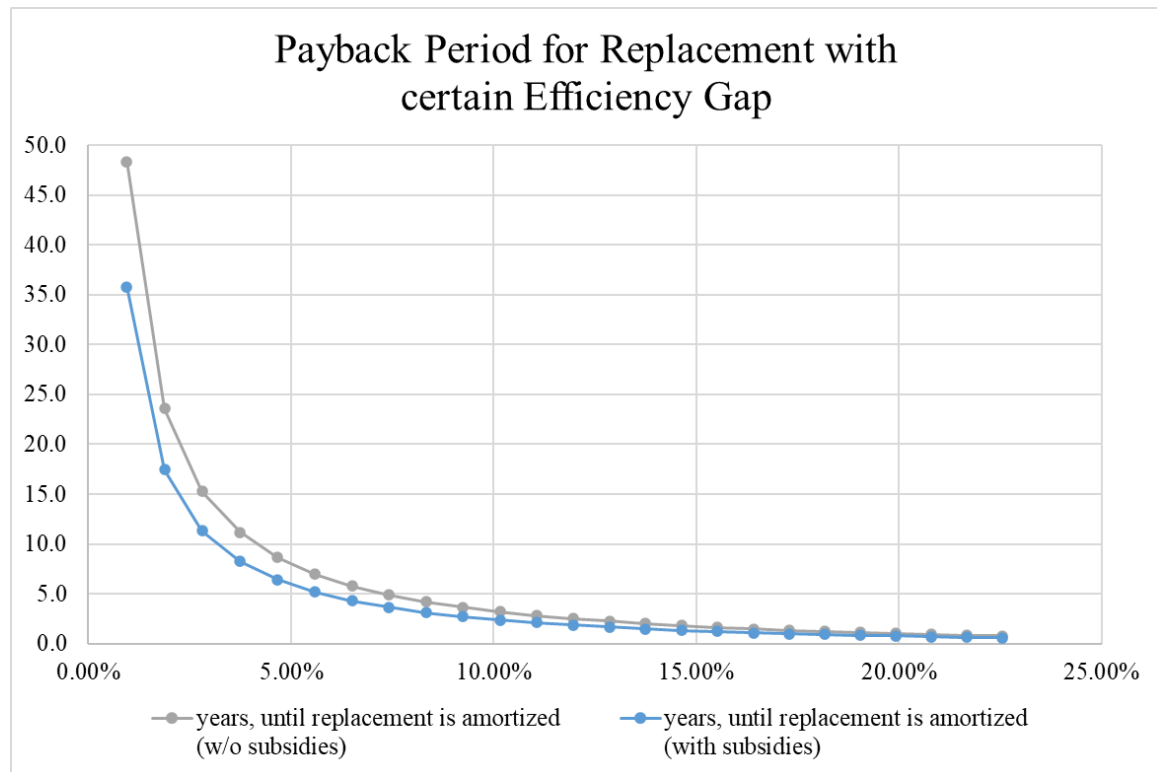


Figure 4-8: Payback Period for Replacement with certain Efficiency Gap

The curves in figure 4-8 are quite similar to those in figure 4-7 but provide more essential insights into the efficiency gap needed to make a replacement economic. Again, the grey curve illustrates the case without subsidies, and the light blue curve the case with subsidies. The first mentionable efficiency gap where the payback period becomes reasonable is at about 5%. In that case, the payback period without subsidies (with subsidies) is circa 7.5 years (6 years). A five-year payback period threshold is undershot at an efficiency gap of 7% without subsidies (around 6% for the case with subsidies).

In conclusion, the spreadsheet calculation and computed graphs emphasize and confirm the assumption that the profitability of PV module replacement is not only given after the end of the panel's lifetime at 25 years but much earlier. When the efficiency increase of new solar technology continues, the replacement will be economically feasible

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in less than eight years. That leads to the assumption that today's forecasts for e-waste volumes from solar panels might be underestimated. As especially utility-scale solar farms are operated for economic reasons, the replacement might be considered when more electricity and money could be generated with the same land area.

This approach will also have a significant influence on LCAs that were conducted for solar systems, as mentioned in section 4.2.1. The GWP hypothesizes an operational time of 25 years and considers the generated electricity over the total lifetime. Early replacement will drastically shorten the lifetime and thus also increase the GWP of solar energy. As the EPBT only ranges from two to four years, the solar system will still pay back the energy needed to build the system and, therefore, still produce green energy. But the energy will not be as green as it could possibly be.

4.3 Experimental Part

This subchapter reports the experimental work and related findings. The first step was to assess the condition of the underlying solar panels donated from RIRRC and quantify the remaining power potential. Unfortunately, the solar panels' front glass had already been shattered, which influenced the experiments' planning, as described later in more detail.

The following three main experiments are described in separated sections

1. Cutting a single solar cell and examining its condition
2. Cutting a certain panel size, examining the condition and recharge a mobile device
3. Cutting of tempered glass specimens

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Within each subsection, challenges that have occurred are mentioned. Finally, the results are summarized, and the significance of the underlying study is emphasized.

4.3.1 The Solar Panels Used for the Study

The solar panels that were donated from RIRRC were monocrystalline silicon panels with 96 cells made by Panasonic. [111] This panel is rated for an output wattage of 330 and an initial efficiency of 19.7%. The particular solar panels were manufactured back in 2004, but this type is still sold by Panasonic. Table 4-3 provides more detailed information about the solar panel.

Table 4-3: Specifications: Panasonic PV Panel VBHN330SA17 [111]

Specifications	Data
Power Output	330 W
Efficiency	19.7 %
Expected annual efficiency degradation	0.26 %
Open Circuit Voltage	69.7 V
Open Circuit Current	6.07 A
Dimension (LxWxH)	62.6 x 41.5 x 1.6 in.
Year of Development	1997

The donated solar panels' front glass was already shattered, which significantly influenced the experiments conducted. As described later in the third experiment, additional tempered glass specimens were worked on to examine the cutting behavior of tempered glass. Figure 4-9 shows details about the solar panels condition.

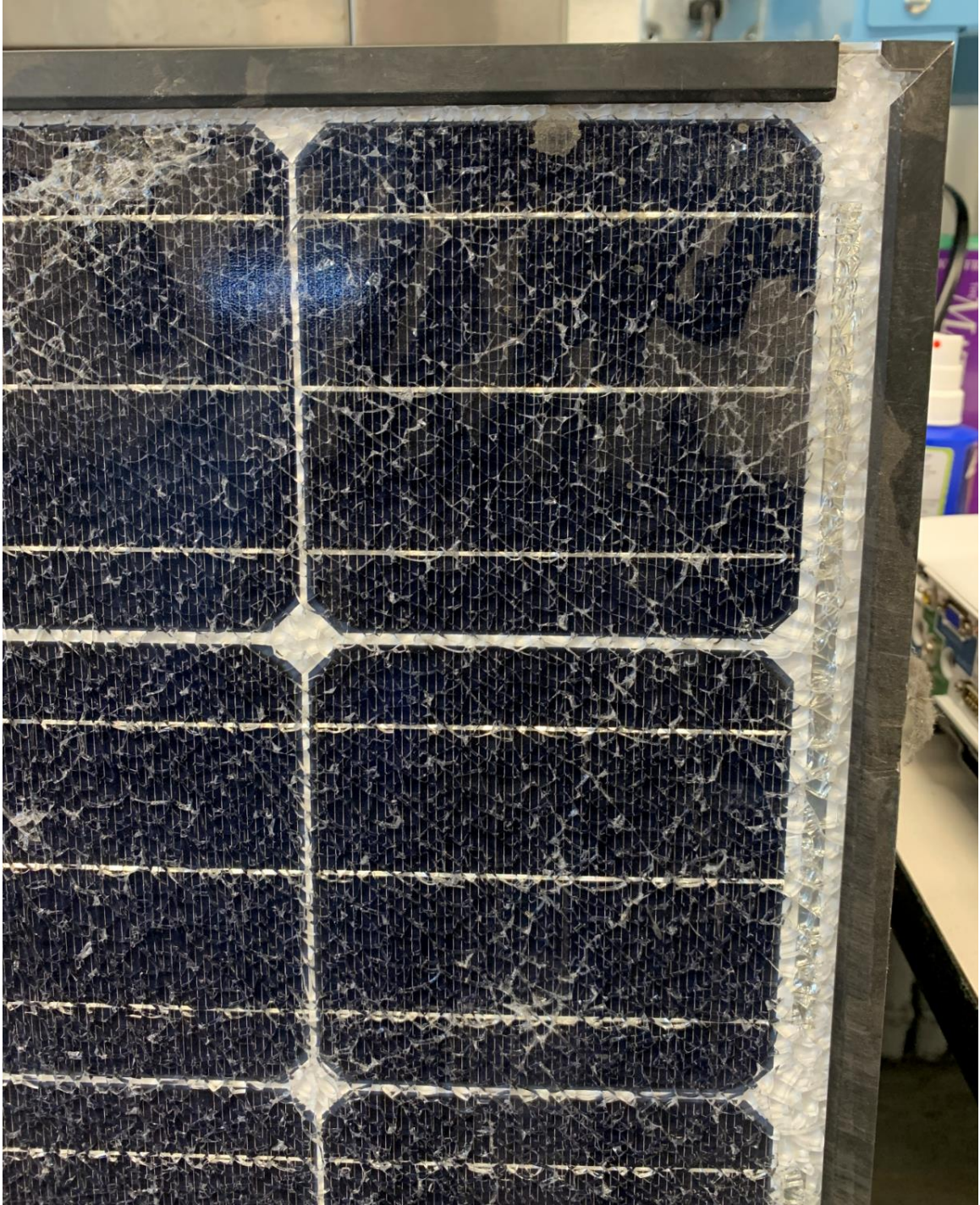


Figure 4-9: Close-Up of the Solar Panel's Condition

Before starting the three main experiments, a test was conducted on whether the panels were still functioning and converting the sunlight into electricity (see figure 4-10). As no detailed information about the current P-V-Diagram characteristics was known, only

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the open-circuit voltage and current were measured. Thus, no adjustable load was used for the measurements. [112]

All the measurements within this chapter were done at the Engineering Lab at the University of Rhode Island on June 6th, 2021, which was very sunny with 30 degrees Celsius and a blue sky.

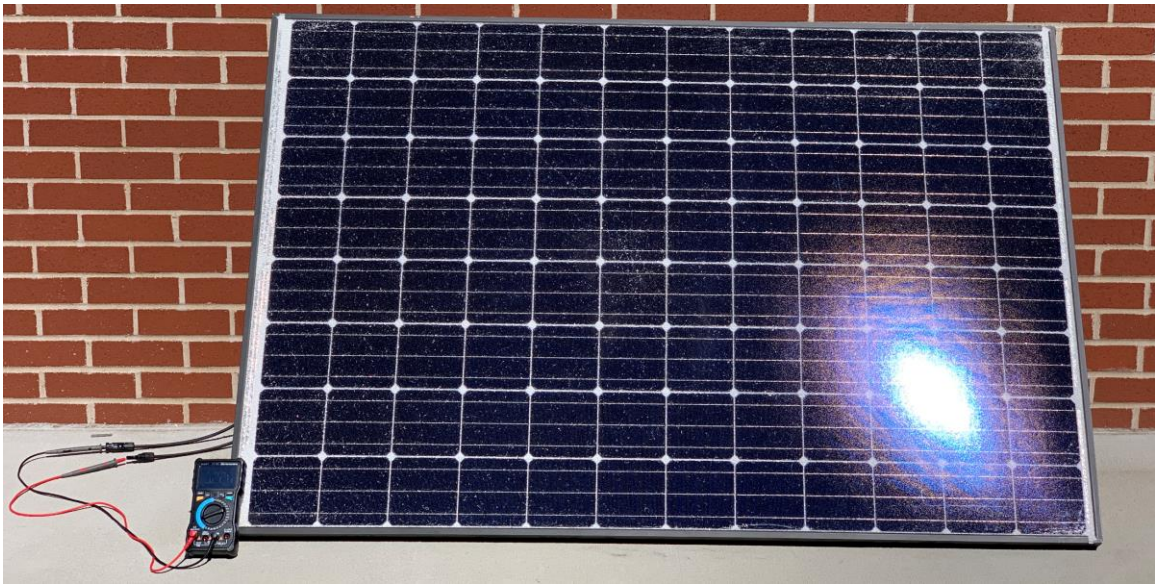


Figure 4-10: *U and I Measuring of the Donated Solar Panel*

The results are summarized in the following table:

Table 4-4: *Actual Power Output of the Donated Solar Panel*

Characteristics	Value
Open Circuit Voltage	66.7 V
Open Circuit Current	5.26 A
Theoretical Power Output (without load)	350.84 W

The power output is still reasonable as the solar panel generates about 83% of the original power compared to the open circuit specifications in table 4-3. However, there could be several reasons for the discrepancy between the original solar panel and the

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measured one. First of all, the 6.07 A, the original solar panel is labeled with as seen in table 4-3, was measured in a laboratory with a determined light irradiance. Further, the shattered glass influences the transparency and handicaps the light transmission through the glass. Another reason could be the silicon wafer condition beneath the glass: the impact that caused the shattering might have also damaged the silicon wafer.

Even if the panel's power output was not measurable, it would have been worth doing the cutting experiments as the cause for the missing power could have been within the conjunction box, the solar cells' connections, or the block diodes, and not within the silicon cells themselves.

4.3.2 Experiment #1

The first experiment was conducted to test whether a single silicon cell will keep its functionality after separation from the whole panel. Further, the characteristics of cutting the shattered tempered glass have to be investigated, and appropriate cutting technology has to be found. Finally, the silicon wafer was examined to analyze its condition beneath the shattered front glass as the fragile crystalline silicon might also be cracked.

In the first trial, a standard rotary tool (Dremel) with a small diamond burr (see figure 4-11) was used to make a small cut around one solar cell.



Figure 4-11: Rotary Tool (DREMEL) with Diamond Burr

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That worked quite well but required much time and produced an uneven cutting edge. Hence, a second trial was conducted with the Dremel Ultra Saw®, a mixture of an angle grinder and a classic rotary tool with a stop to adjust the cutting depth (see figure 4-12).



Figure 4-12: DREMEL Ultra Saw®

Equipped with a diamond blade, it was possible to execute very precise cuts with a determined depth in a short time. However, that helped to only cut as deep as the glass thickness to prevent the polyvinyl fluoride back foil from melting and sticking around the diamond blade. That would have produced hazardous smoke and handicapped the glass cutting.

On the other hand, the blade is too wide to cut along the small gap between two silicon cells without touching the silicon cells themselves. Hence, the cut was executed with a bit of offset not to destroy the wafers. For future applications, thinner blades would be necessary. The final cut through the foil was made with a standard saw blade attached

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to the Ultra Saw®. As a result, a single solar cell with even cutting edges was separated from the remaining panel (see figure 4-13).

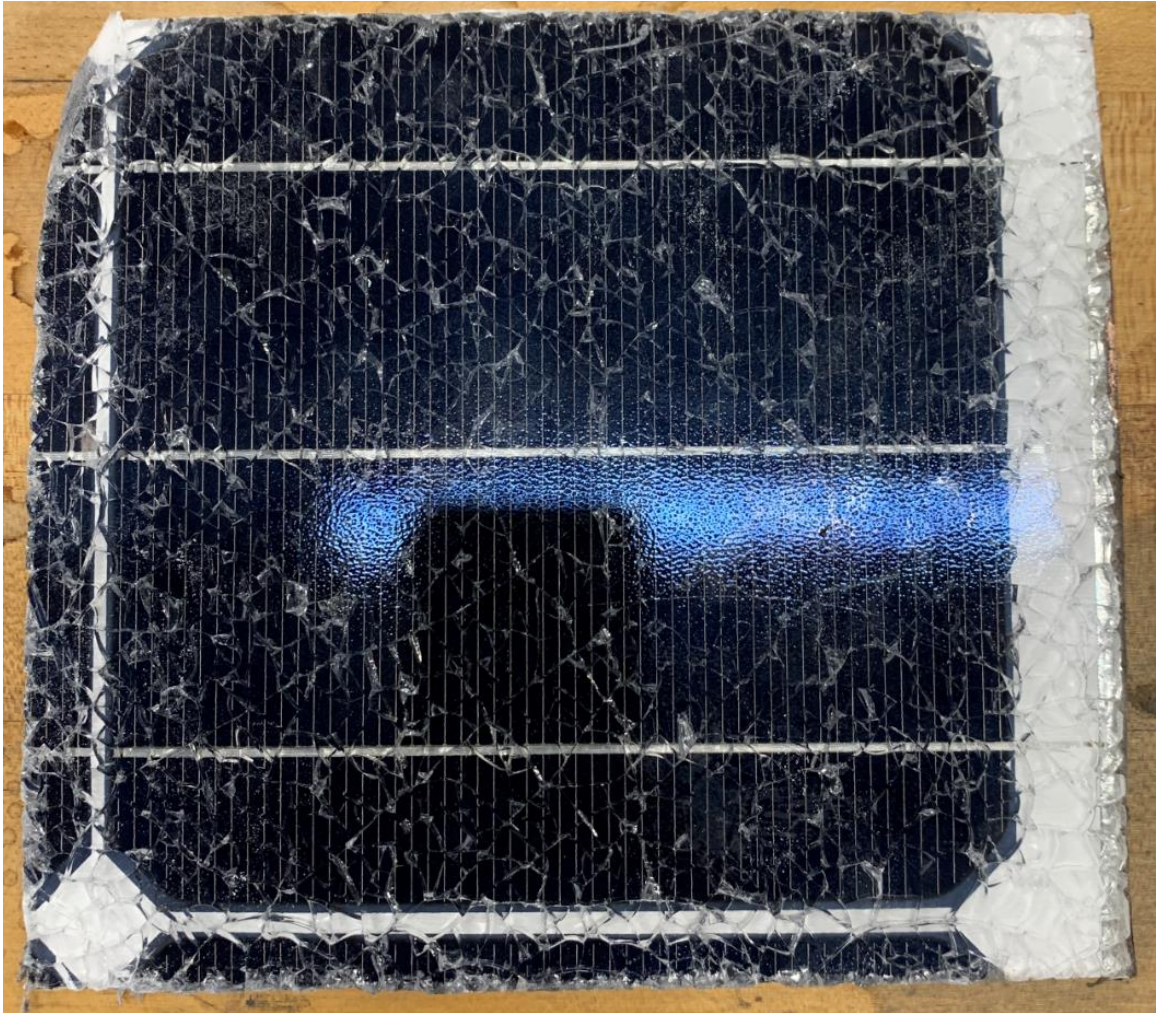


Figure 4-13: A Single Solar Cell Cut from the Original Panel

The single solar cell detached from the whole panel became slightly curved due to the broken glass and the lack of rigidity due to the missing aluminum frame.

Next, the solar cell was checked for proper operation. Firstly, the back cover was removed locally to access the bus bars as the plus pole is at the solar cell's rear. The minus pole is at the front side and is accessible via the bus bars at one cutting edge, where the

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upper bus bars go down to attach to the lower side of the neighboring solar cell (see figure 4-14).



Figure 4-14: Solar Cell Cutting Edge

Secondly, the open-circuit voltage and current were measured with a multimeter. The results are shown in table 4-5.

Table 4-5: Actual Power Output of Single Solar Cell

Characteristics	Value
Open Circuit Voltage	0.69 V
Open Circuit Current	1.80 A
Theoretical Power Output (without load)	1.24 W

The open-circuit voltage of the single cell is 0.69 V which roughly matches the voltage of the entire panel divided by 96. The actual current is lower and leads to a theoretical power output of 1.24 watts. The difference to the open circuit current from the entire panel (see table 4-4) might occur due to the bending after the cutting procedure. The bending could have caused micro-cracks within the crystalline silicon.

To investigate the condition of the silicon wafer, the glass has to be removed. That is possible by heating the cell to melt the ethylene vinyl acetate (EVA) foil that holds the

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various material layers together. Two tests were run, and a small industrial oven was used to heat the cells. In the first test, the cell was heated up at 220 degrees Celsius for ten minutes. The cell came out heavily bent, significantly influencing the wafer's condition (see figure 4-15). However, removing the glass was very tough as the EVA was still very sticky. The silicon wafer broke into small pieces by removing the glass, making it impossible to determine what has caused the wafer's fracturing.

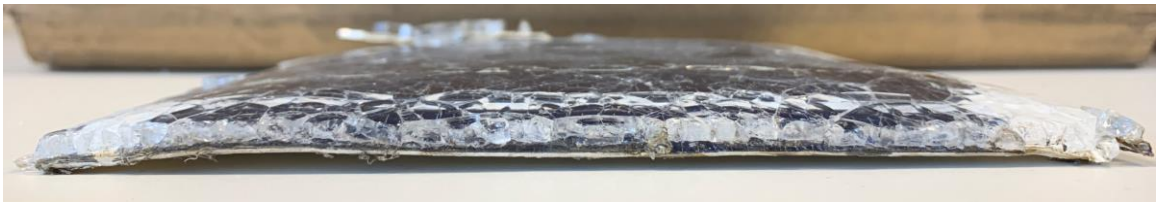


Figure 4-15: Single Solar Cell after Heating Procedure

The result of the second test was not much better. Heating the cell for 20 minutes at 220 degrees Celsius made removing the glass more manageable, but the wafer still broke due to the physical force needed to pull apart the glass pieces.

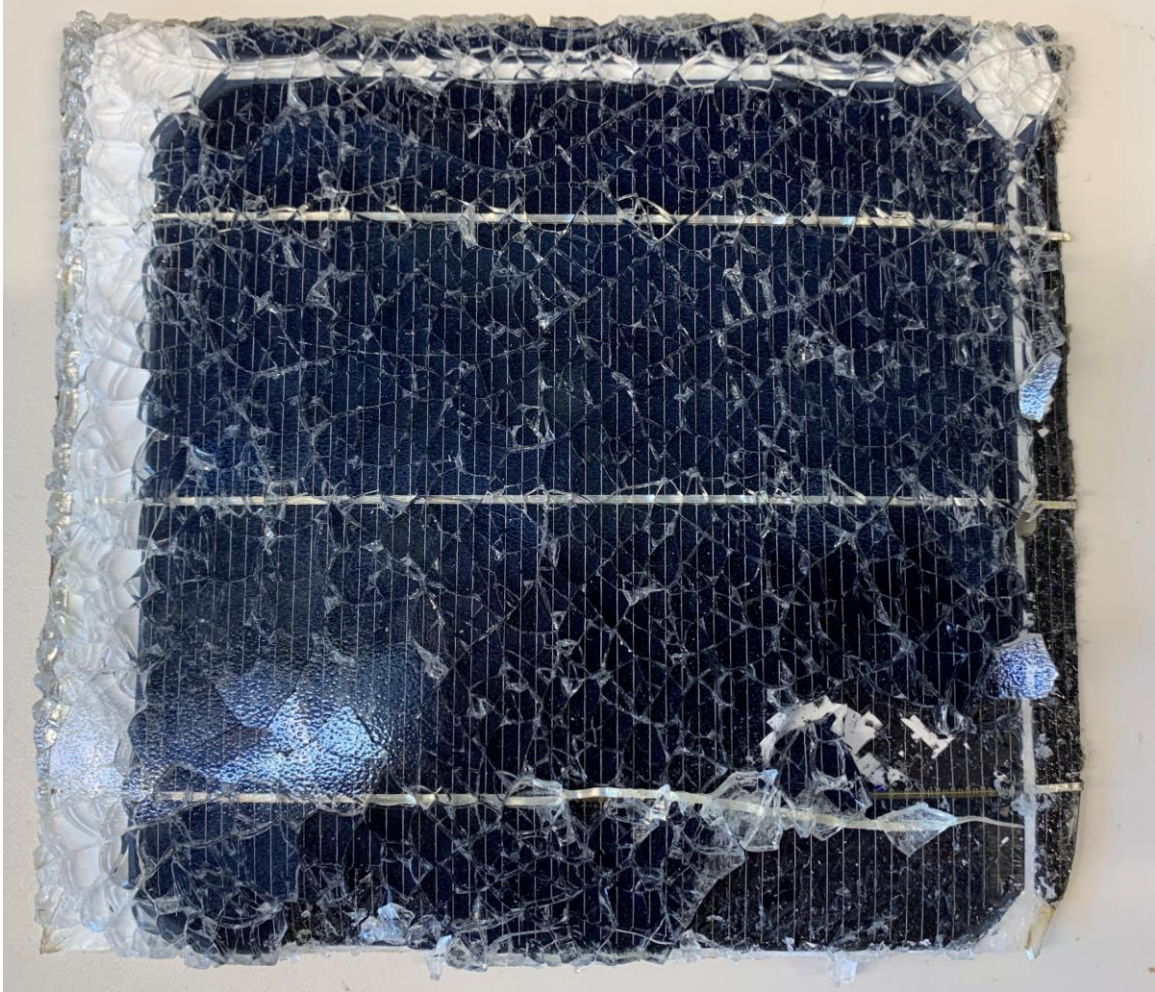


Figure 4-16: Solar Cell after Heating Procedure and Glass Removing

As a result, it was not possible to determine whether the wafer was broken before the cell was heated up or not. Therefore, the investigation of the wafer's condition was shifted into the next experimental section.

4.3.3 Experiment #2

The second experiment picked up the ideal cutting method from the first row of experiments. Hence, the Dremel Ultra Saw® was used to conduct all cuts related to this test. The goal was to build a stand-alone solar system prototype with a subpart of the used solar panels to charge smartphones, tablets, or other mobile devices. Firstly, a section from

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the solar panel that produces around 20 V has to be separated, as 20 V is the optimal input voltage for the used solar charge controller for 12 V batteries. The 12 V battery is used to buffer the electrical energy. Secondly, the solar cells must be reconnected to one string, and the power output must be evaluated. Further, the investigation of the wafer condition beneath the shattered glass has to be picked from the previous section.

Every single solar cell of the module generates about 0.7 volt (see section 4.3.2). Therefore, several shapes are possible to conform a smaller solar panel that produces around 20 V. There could be, for example, a 5×6 shape with 30 cells that add up to 21 V or a 4×7 shape with 28 cells that adds up to 19.6 V. However, a 4×7 array was cut from the original 96-cell PV module. The resulting 28-cell module then had four single strings of seven solar cells each. To reconnect them to one proper string, the end of each string was connected to the following string to generate an s-shaped complete string of 28 solar cells, as figure 4-17 illustrates.

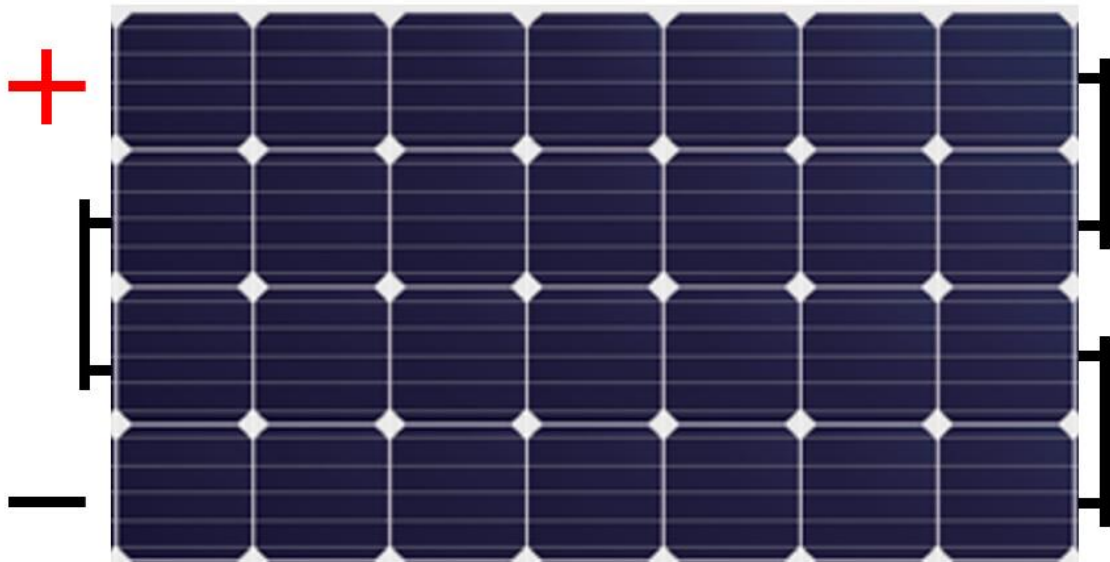


Figure 4-17: Reconnected Solar Cell String with 28 Cells

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Every bus bar on the cell (three on the particular cell type) was soldered together to connect every cell properly. Copper wire was used as a bridge between the bus bars. Prior to reconnecting the cells, the back foil was locally removed to uncover the bus bars as in the first experiment.

The remaining unconnected endings form the plus pole (lower side of the solar cell at one end of the string) and minus pole (upper side of the solar cell at the other end of the string) of the new PV module. Afterward, the open-circuit voltage and current were measured with a multimeter to evaluate the new module's power potential. Figure 4-18 shows the resulting solar panel and the experimental setup.

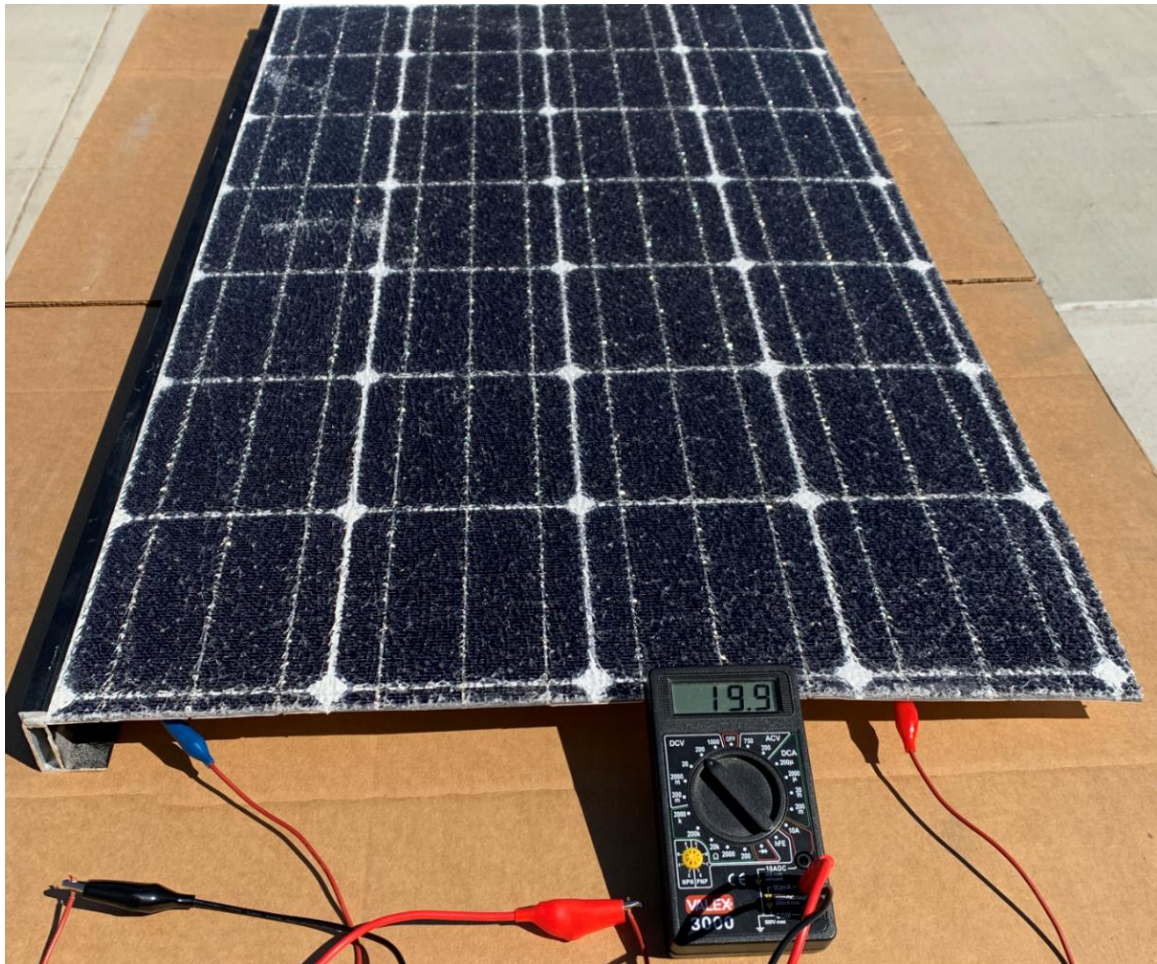


Figure 4-18: 28-cell PV Panel Measuring Set-Up

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Further, table 4-6 summarizes the 28-cell module's characteristics.

Table 4-6: Actual Power Output of 28-cell Solar Module

Characteristics	Value
Open Circuit Voltage	19.9 V
Open Circuit Current	4.57 A
Theoretical Power Output (without load)	90.94 W

The voltage roughly matches the expected value of 19.6 V ($28 * 0.7 V$), while the current has a value of 4.57 A. Hence, the 28-cell module has a slightly lower current output than the entire solar panel had (see table 4-4).

Unfortunately, the 28-cell module was too big for the lab's industrial oven, so that the silicon wafer could not have been investigated by heating the module and removing the glass. However, interesting findings have been made when the module was moved into the sunlight. Several cracks within the silicon wafer were visible in the closer area around the impact areas, where something caused the tempered glass to shatter. Those cracks are significantly distinguishable from the small cracks within the shattered glass, as the following figure shows.

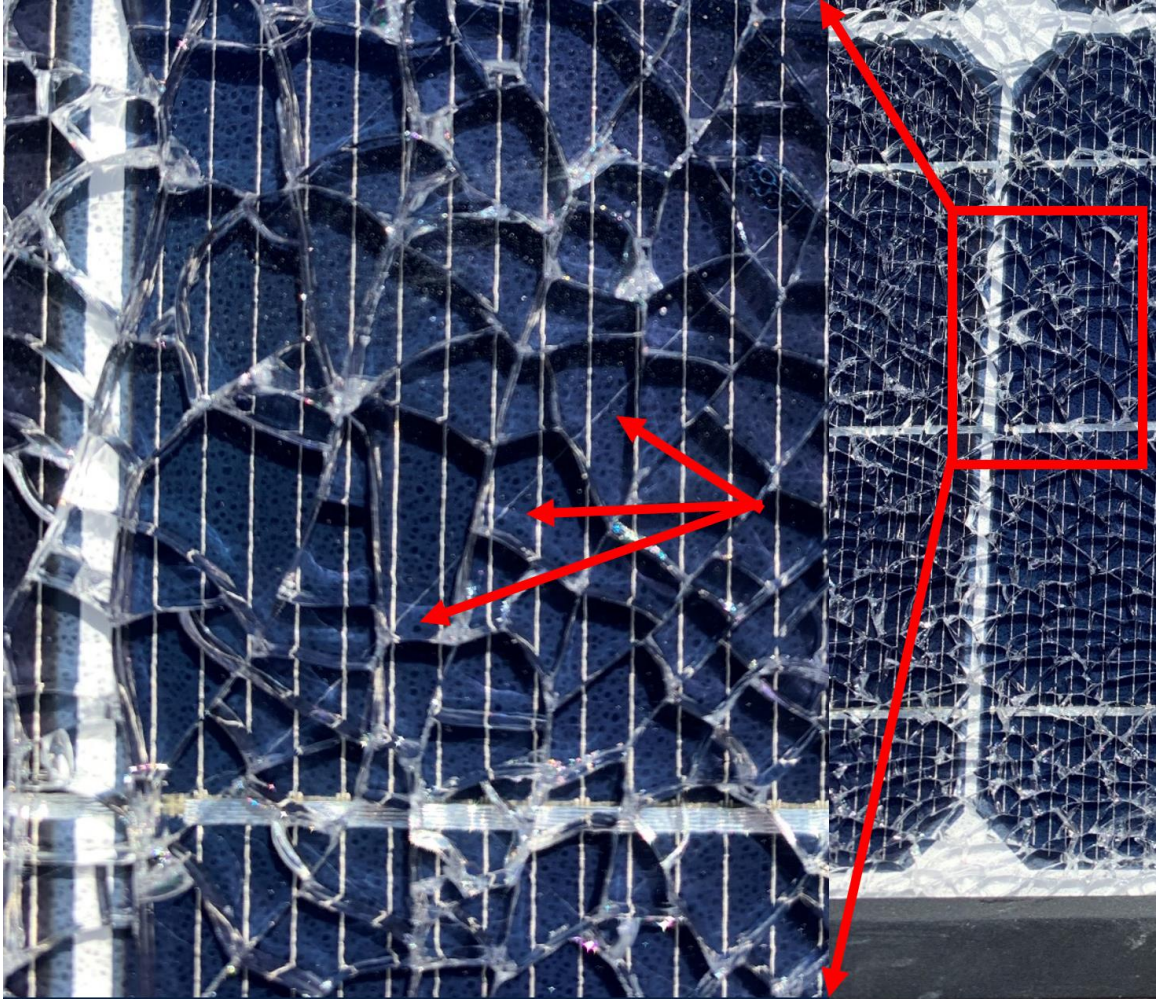


Figure 4-19: Visible Cracks within the Silicon Wafers

Figure 4-19 shows a zoomed detail of the solar panel, and the red arrows mark the path of the crack within the silicon wafer. There might be further micro-cracks among those visible cracks that are not visible to the naked eye. However, those cracks significantly influence the solar panel's efficiency. In future processes, the visible cuts could be detected automatically with image data processing. Hence, those direct impact areas could be omitted to reduce the efficiency loss of the created panel.

Another finding of the experiment is the immense stability loss of the cut panel due to the shattered glass. If the panel experience to extreme bending, further cracks within the

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brittle silicon wafer will occur. Thus, the solar panel was supported below while the cut was made to prevent it from bending. Nevertheless, additional cracks must have occurred as the actual current output of 4.57 A is lower than the current from the entire solar panel, as mentioned above (see table 4-4).

Afterward, the 12 V charging controller was connected to the panel's plus and minus poles, and a mobile device was successfully charged during the experiment.

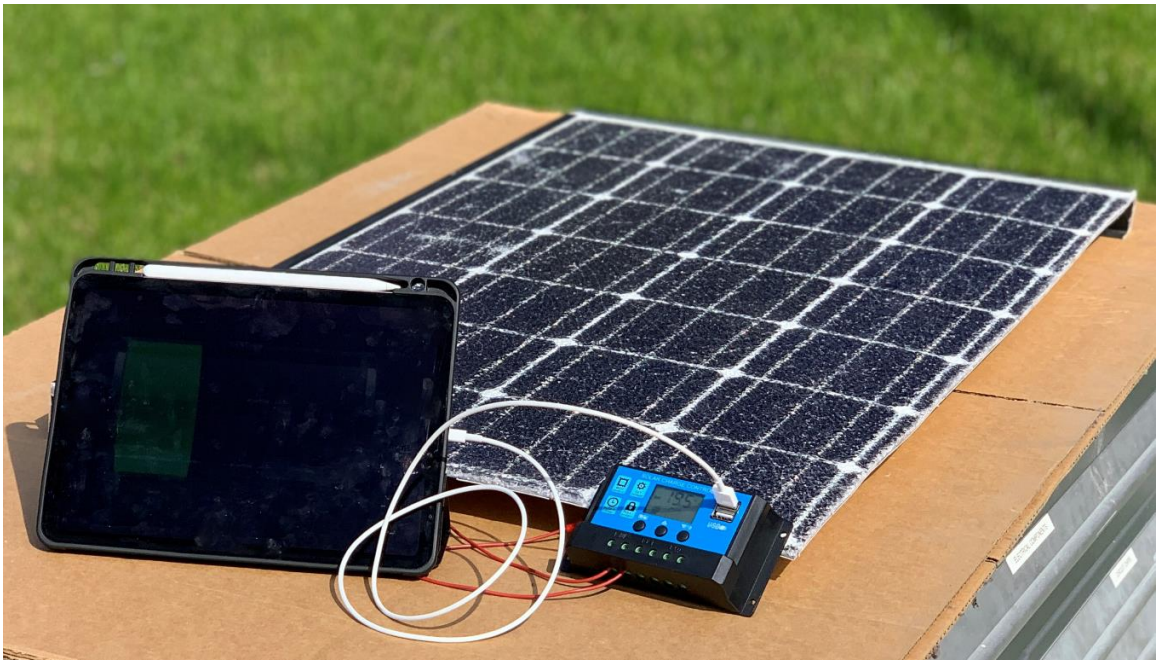


Figure 4-20: Successful Charging of a Tablet with a Repurposed Solar Panel

By adding a 12 battery, a stand-alone system could be built, as the following pictogram shown in figure 4-21 illustrates.

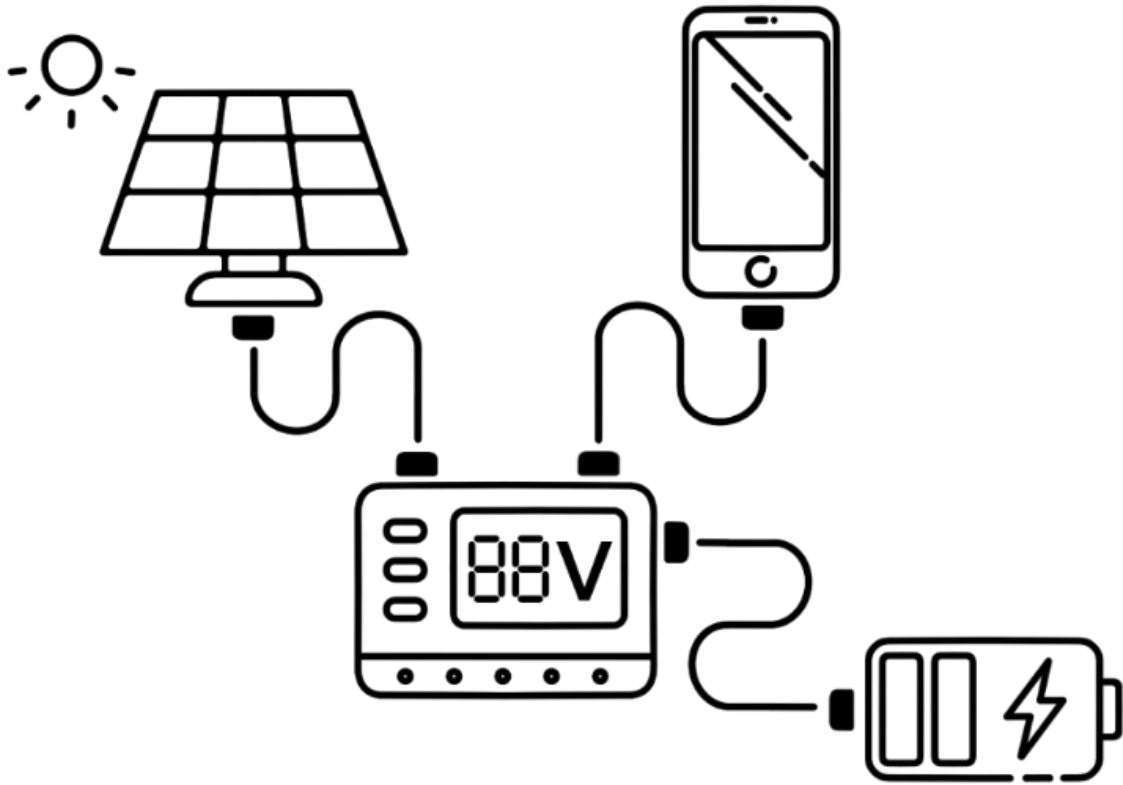


Figure 4-21: Illustration of a Charging Hub with Second-Life Solar Panels

Adding an inverter to the load output of the charging controller could change the voltage from 12 V to 110 V to complete the power hub with standard home outlets.

Finally, the 28-cell module was supplied with a new aluminum frame (see figure 4-22). The frame reinforces the module and rebuilds the stability. The new total 35.82 in. in length and 21.26 in. in width and, therefore, much more portable than a panel in original size (see table 4-3).

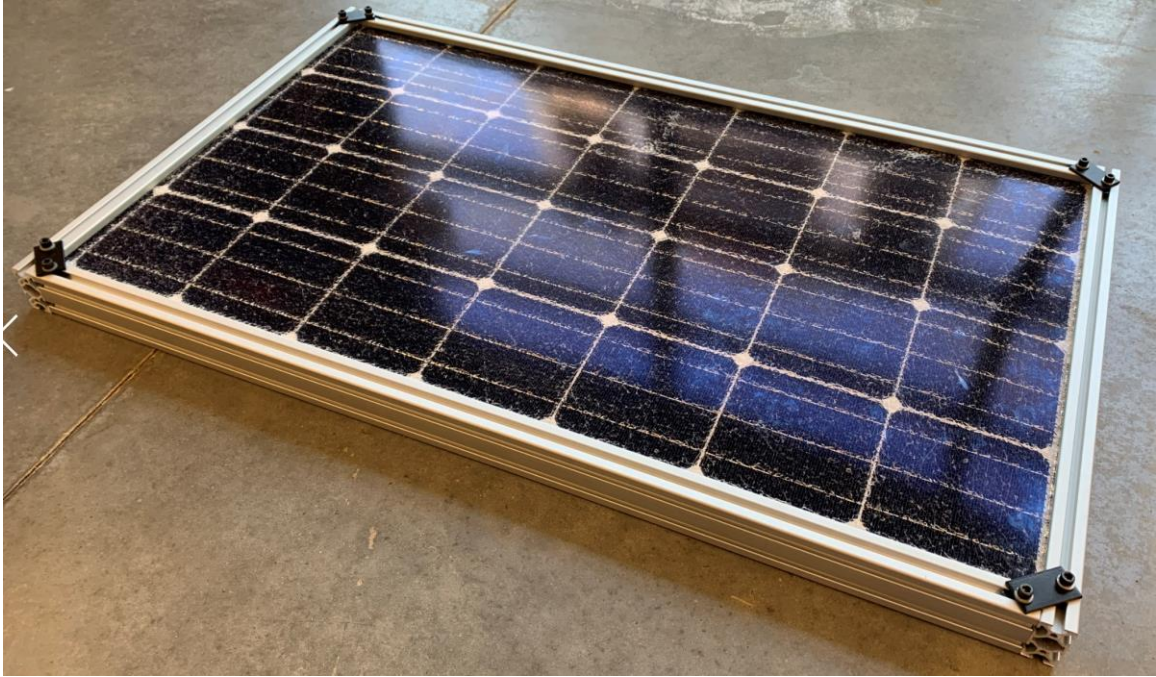


Figure 4-22: 28-Cell Module with New Aluminum Frame

Further, resealing would be necessary to restore the encapsulation and making the new module ready for outdoor usage. However, resealing is not part of this study.

4.3.4 Experiment #3

In the previous experiments, no insights into the behavior of tempered glass could have been made, as the solar panel's front glass was already shattered. Nevertheless, the behavior of tempered glass, when it is cut with conventional cutting technologies, should be investigated. Hence, small tempered glass specimens were ordered to enable cutting tests with tempered glass. The goal is to prove the common expectation that tempered glass would instantly shatter when a physical force from a cutting tool is applied.

The specimens have about the same thickness as the PV panels' glass (3.5 mm). Two tools were used trying to cut the tempered glass without shattering it into tiny pieces. In each run, one tempered glass sheet was clamped on the working table.

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Firstly, the rotary tool with a small diamond burr from section 4.3.2 was used. Unlike the expectations, the shattering did not happen instantly at first contact, but after some millimeter grinding into the glass. The occurring heat or physical impact might have caused the tempered glass to shatter. Figure 4-23 shows the tempered glass specimens before (left picture) and after the test (right picture).

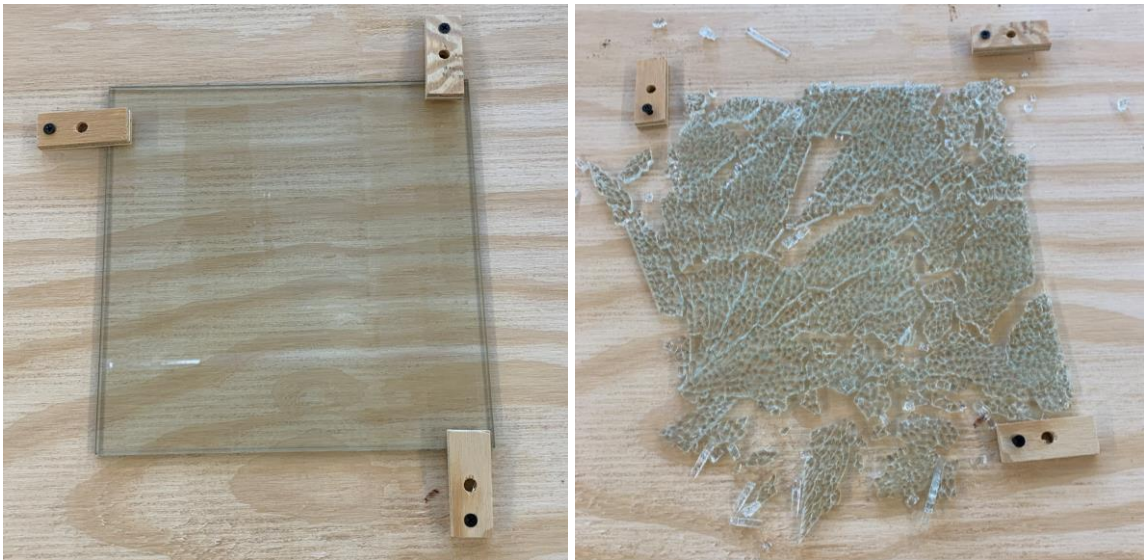


Figure 4-23: Cutting Test of Tempered Glass

In the second run, the Dremel Ultra Saw® that worked well in the previous experiments was used. The results were quite the same as those in the first run. After some moments of grinding, the glass shattered again.

As a result, the hypothesis that the cutting of tempered glass with conventional cutting technologies would not work could be confirmed. Therefore, a reasonable and necessary follow-up study should examine applying a powerful laser cutter to cut tempered glass.

4.3.5 Experimental Results

This section summarizes the findings from the three main experiments.

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First of all, shattered front glass on solar panels does not mean a complete loss of functionality. The remaining power output was measured and resulted in about 83% of the original power. Hence, even those panels qualify for second-life use cases.

Further, the cutting of shattered solar panels worked well with a diamond cutting blade (experiments #1 and #2), unlike the cutting of intact tempered glass (experiment #3). With a proper resealing technology, even the diamond blade cutting of solar panels with intact glass becomes reasonable. The glass's shattering would not matter, as the encapsulation could be restored afterward. In that case, no damage within the silicon wafer would occur, and the resulting panel's power output would be better. Nevertheless, even though several encapsulation techniques are discussed in solar panel forums [113], [114], the optimal resealing approach must be found first and could be examined in a follow-up study.

Another uncertainty was whether it is possible to reconnect the solar cells of the cut solar panel to one proper string to get the current out. The experiments emphasize the feasibility as the back cover can be removed locally with a rotary tool. When the bus bars become accessible, connection wires can be soldered onto them, and the reconnection is finished.

The most exciting finding is the remaining power output of the repurposed 28-cell module. Even though cracks were identified within the silicon wafers, the 28-cell module still produces around 90 watts in an open circuit measurement. Hence, it would provide plenty of energy to charge a 12 V battery and several mobile devices.

Some of the cracks within the silicon wafers are visible to the naked eye, which was another important finding during the experiments. However, as those visible cracks only

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occur in the surrounding area of the direct impact on the glass, cutting algorithms could omit those areas.

Several outlooks for further studies are imaginable. First of all, the cutting experiments, especially for solar panels with intact tempered glass, have to be repeated with a proper laser cutting machine. The challenge is to find a laser machine with a working area large enough to fit a standard-sized solar panel. Beforehand, a smaller laser machine could be used to investigate the behavior of tempered glass specimens.

Furthermore, the remaining power output of solar panels with shattered glass should be measured when a load is applied. A variable load could then be used to create the P-V-Diagram and evaluate the remaining power output more appropriately. In addition to that, there is a method to investigate the solar panel's condition with an infrared camera. Areas with technical and physical damage like cracks within the silicon wafers, for instance, could be detected as those areas will be getting hotter due to higher internal resistance.

[112]

Chapter 5

5 The Optimal Cutting Strategy

Within the literature review in chapter two, several approaches for the P&C problem are introduced. Chapter five picks one method to investigate the potential to generate cutting patterns to cut solar panels.

The 2D BPP algorithm introduced by Cid-Garcia and Rios-Solis is chosen as it supports the rotation of items to find an optimal solution.

In the following subchapters, a short introduction to Python and the programming environment Jupyter Notebooks is given. Afterward, the methodology of the 2D BPP is described in more detail. Further, the implementation in Python is illustrated and evaluated with an example where 60-cells solar panels have to be cut into smaller pieces.

5.1 A Brief Introduction to Python

All algorithms within this study are programmed in Python 3 and implemented with Jupyter Notebooks [115]. Python 3 is an open-source and multipurpose programming language that can be used for desktop and web applications, as well as scientific numeric problems like data mining or linear programming. [116] The programming language's flexibility is mainly achieved by Python-specific standard libraries, which include pre-coded routines and functions. In addition, there are thousands of third-party libraries that extend the variety of application cases. [117] Jupyter Notebooks is a web application that is commonly used to document and execute Python code. One of the main advantages is the structure which is based on cells. Each cell can contain either code or narrative text and

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be run exclusively while data is shared between cells (e.g., global variables). That enables a very structured way coding and documenting. [115]

In this particular study, two libraries were used: NumPy [118] and PuLP [117]. NumPy is a famous library for scientific programming, especially when it comes to linear algebra. It is mainly powerful in dealing with arrays and has several mathematical, logical, shape manipulation, sorting, selecting, basic linear algebra, and many more routines. The other library, PuLP, contains routines and functions to describe and compute mathematical programs in Python. It runs on any Python interpreter and supports open-source and commercial solvers like PuLP-CBC, GUROBI, CPLEX, MOSEK [119]. The main advantage compared to other solver libraries like SciPy is the way variables and constraints can be described. Instead of matrices, variables and constraints can be defined in a similar expression to the original mathematical form. [117]

5.2 Application of a 2D Bin Packing Problem

The literature review in subchapter 2.2 mentioned the positions and covering algorithm published in the PLOS ONE journal, in 2020, by Cid-Garcia and Rios-Solis. That program was created to solve the two-dimensional bin packing problem (2D BPP) but is well adaptable to a cutting stock problem, as mentioned in chapter two. The primary approach is to find the minimum number of two-dimensional bins (larger rectangle or stock rectangle), all demanded small rectangular items fit into. It is an optimal solution approach that includes the rotation of items by 90 degrees. The rotation increases the number of feasible solutions and, therefore, the possibility to find an optimum. On the other hand, the adaptability for large problems is limited. [52] Whether the performance is sufficient for the underlying problem or not will be investigated in section 5.1.3.

Further, the approach does not care about cutting constraints. But it can be applied as a cutting stock problem if non-guillotine cutting is possible. For the non-guillotine cutting of PV modules a laser cutting technology is compulsory.

The following subchapters will describe the methodology, the implementation in Python, and the results concerning the applicability. The complete Python code is attached in appendix 7.2.

5.2.1 Methodology

The “positions and covering” program is, as the name implies, divided into two stages. The first stage – the positioning stage – discovers all items’ feasible positions within the stock bin. The second stage – the covering stage – is an ILP model that finds the optimal combinations of item positions within all feasible positions while fulfilling the demand for each item.

The first stage

The main idea is to enumerate the integer points within a stock bin with the dimension $H * W$ in the way as shown in the following figure:

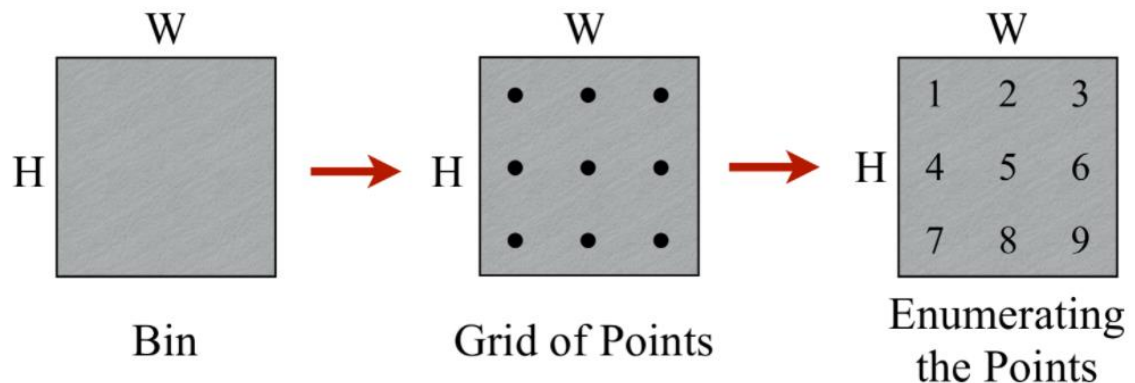


Figure 5-1: Enumerating the Points within the Stock Bin, an Example [52]

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The same methodology is used to enumerate the points for all items $i \in I$ with the dimensions $h_i * w_i$. [52] This grid of points is excellent for the underlying study as each point is well relatable to a solar cell within a solar module.

After the enumeration procedure, a correspondence matrix $C = \{c_{jp}\}$ is created where $p \in P$ indicates the point within the stock bins grid of points and j a feasible position for an item i . Hence, every $j \in J$ is a row, and every $p \in P$ is a column within the matrix C . If $c_{jp} = 1$, the position j includes point p , otherwise $c_{jp} = 0$. The subset $T(i)$ stores a position j if it is a feasible position for item i . [52]

Cid-Garcia and Rios-Solis consider the item rotation as a separate decision procedure within the whole program. They create a second correspondence matrix $\bar{C} = \{\bar{c}_{jp}\}$ and a particular decision variable for rotated items later within the ILP. [52]

In this study, the rotation is included within the correspondence matrix C and considered as another feasible position j for item i . Hence, item i is considered as $h_i * w_i$ or $w_i * h_i$ as long as $h_i \neq w_i$. As a result, the number of rows within the matrix C can almost double.

The second stage

The covering stage is an ILP model that tries to find a feasible position to fit all demanded items into a minimum number of bins. Therefore, two additional inputs are necessary. The demand d_i for each item i and a starting number of bins.

The number of bins to start with is the minimum number of bins K calculated by simply dividing the sum of the total area of all items by the area of the stock bin. In this case, a perfect fit of all items is assumed. In this calculation, the demand d_i for each item

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i is essential as it significantly influences the required area. Cid-Garcia and Rios-Solis omit the demand for each item in their formula, which is a mistake. [52] However, the following formula shows the calculation of the minimum number while including the demand.

$$K = \frac{\sum_{i \in I} h_i * w_i * d_i}{H * W} \quad (4)$$

Different from Cid-Garcia and Rios-Solis, just one decision variable x_{jp}^i is defined as all positions, whether rotated or not, are stored within one matrix. It is a binary variable, where $x_{jk}^i = 1$ if the position $j \in T(i)$ of item i in bin $k \in K$ is chosen, otherwise $x_{jk}^i = 0$.

There is no objective function, as the ILP only aims to a feasible solution for the smallest K . The ILP starts with K obtained from the formula above (4). If there is no workable solution, K is increased by one, and the ILP is repeated. The positions stage must not be computed again.

The ILP has three constraints that are defined as follows:

$$\sum_{i \in I} \sum_{j \in T(i)} c_{jp} * x_{jk}^i \leq 1, \quad \forall p \in P, \forall k \in K \quad (5)$$

$$\sum_{j \in T(i)} \sum_{k \in K} x_{jk}^i \geq d_i, \quad \forall i \in I \quad (6)$$

$$x_{jk}^i \in \{0, 1\}, \quad i \in I, \quad j \in T(i), \quad k \in K \quad (7)$$

Equation (5) ensures that a point p within a bin k is not covered by more than one item i whether the item has been rotated or not. The second constraint (6) focus on the demand d_i for each item i that has to be fulfilled with a higher or equal-to constraint. Further, the decision variable x_{jk}^i , in (7), is a binary variable and can either take the value one or zeros. [52]

5.2.2 Implementation in Python

The first step of implementing the described methodology is to generate several input data. Hence, the first section within the Jupyter Notebook defines all required input data.

In the first place, the height (H) and width (W) of the stock rectangles (the solar panels), the dimensions of the required smaller rectangles, and the demand for each required shape are defined. The small rectangles' dimensions are stored in a two-dimensional NumPy array named $items_I = ([h_i, w_i])$, while the demand for each item is stored in a separate one-dimensional array. Afterward, the points within the stock rectangles are enumerated to create a cartesian grid, and the correspondence matrix C as well as the subset $T(i)$ for each item i is initialized. Figure 5-2 shows the cartesian grid for a standard-sized solar panel with 60 cells.

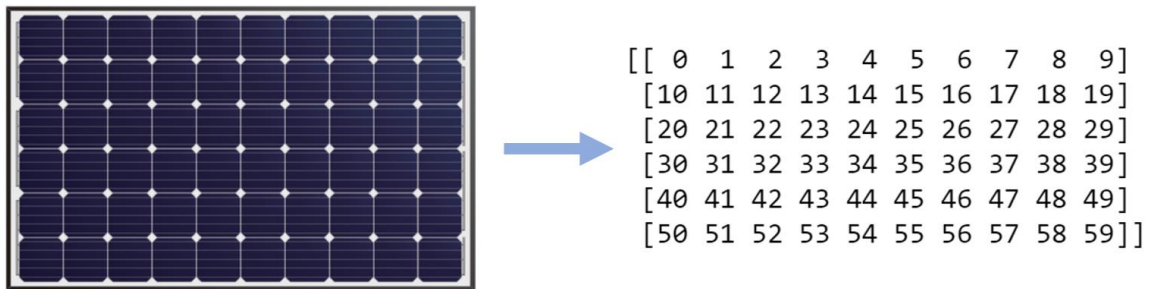


Figure 5-2: Enumerated stock rectangle (standard-sized 60-cell solar panel)

Secondly, the positioning algorithm is programmed. It is a combination of several for-loops and if-statements to create the substantial correspondence matrix C_{jp} . The outer for-loop repeats the successive calculation for every item in $items_I$. Firstly, the width and height of the particular item are calculated and used for the subsequent if-statements. Now, for every point in the stock rectangle's total width, a check is made whether the item's width fits into the remaining width of the stock rectangle. An analog check is made for the

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height. If the item fits into a certain position within the stock rectangle, the corresponding points (p) are stored in an added row (j) within the C_matrix by setting the indices equal to 1 ($c_{jp} = 1$). Additionally, the row index for the particular item position (j) is added to the subset $T(i)$ of feasible positions for item i . The following table shows an example for the C_matrix .

Table 5-1: C -matrix Example

		Points p													
		0	1	2	3	4	5	6	7	8	9	10	11	[...]	59
Positions (j)	1	1	1	1	1	1	0	0	0	0	0	0	0	[...]	0
	2	0	1	1	1	1	1	0	0	0	0	0	0	[...]	0
	3	0	0	1	1	1	1	1	0	0	0	0	0	[...]	0
	4	0	0	0	1	1	1	1	1	0	0	0	0	[...]	0
	5	0	0	0	0	1	1	1	1	1	0	0	0	[...]	0
	[...]														

Afterward, the algorithm is repeated to include the rotation part while the item's width and height dimensions are interchanged. As mentioned in the previous subchapter, the rotation makes no sense if the width and height are equal. Hence, an if-statement is added to focus on items with h_i not equal to w_i .

Figure 5-3 shows the algorithm's primary logic that has been described above. The whole code is attached in the appendix 7.2.


```

1  for item in items_I:
2      # calculate width (wi) and height (hi) of item i
3      # check the width of item
4      for l in range(0,W):
5          if l+wi <= W:
6              # check the height of item
7              for h in range(0,H):
8                  if h + hi <= H:
9                      # add a row to C_matrix
10                     # store the item's position in C_matrix
11                     # store row index in subset T(i)
12
13     #ROTATION
14     if hi != wi:
15         # check the width of rotated item
16         for l in range(0,W):
17             if l+hi <= W:
18                 # check the height of rotated item
19                 for h in range(0,H):
20                     if h + wi <= H:
21                         # add a row to C_matrix
22                         # store the item's position in C_matrix
23                         # store row index in subset T(i)

```

Figure 5-3: Basic Logic of Positioning Algorithm

An essential input data for the Covering ILP model is the minimum number of stock rectangles (bins), as this will be the starting point for the algorithm. Thus, an independent function *getK()* is coded to compute the formula (1) mentioned above. As the number of bins has to be an integer, the function uses a particular NumPy routine to round up the result once no integer number was calculated.

At this point, all relevant data for the ILP is created, and the ILP can be formulated. As mentioned before, computing the ILP depends on the number of bins K as K directly influences the number of variables and the formulation of the constraints. Therefore, the ILP is separated into two phases:

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In the first phase, the ILP is run with the minimum number of bins generated by the function *getK()*. The decision variables are initialized and stored within a three-dimensional array as the decision variable depends on three indices (number of bins, number of items, number of positions). Afterward, the constraints are generated within several for loops to cover all points $p \in P$ and bins $k \in K$ for the first constraint (2) and all items $i \in I$ for the second constraint (3). The standard solver within the PuLP library then solves the problem and returns one value of the following set of status values:

Table 5-2: returned status of PuLP standard solver

Value	Description
-1	No feasible solution
0	Not solved
1	Optimal solution
2	Unbounded
3	Undefined

The first phase's result is checked within an if-statement whether the optimal solution has been found or not. If not, the algorithm enters the second phase and goes into a while loop to conduct several iterations of the ILP while the number of bins increases by one in every iteration. Variables are only added for the newly created bin to avoid duplicated variables names. In the constraints' case, it is impossible to add the constraints for the additional bin as the second constraints directly depend on the number of bins. Hence, the whole constraint formula will change. Therefore, all previous constraints are deleted and generated again within each iteration.

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The ILP is solved again, and the algorithm enters a new iteration within the while loop until the solver status is equal to one and the optimal number of bins (stock sheets) is found.

5.2.3 Example and Results

Not many papers dealing with cutting stock approaches neither explain the application of the developed algorithms nor demonstrate examples that are reasonable in reality. That also applies to the computed algorithm described above. The solver just returns the status of the solution and an impractical list for the values of all decision variables and constraints. It would be necessary for the proper application to have an easy-to-understand cutting list for each stock sheet. How this could be managed with Python for a particular example is described in the following paragraphs.

The Application Case

As previously shown in figure 5-2, the stock sheets are commercial standard-sized 60-cells solar panels that might have been discarded for a specific reason. The goal is to determine the number of solar panels needed to remanufacture them into several smaller panels with a certain demand per panel. The following table 5-3 shows the items and their demand.

Table 5-3: Input data for demanded items

#	Dimension [$h_i * w_i$]	Demand [d_i]
1	3 x 5	24
2	6 x 2	10
3	4 x 7	30
4	2 x 5	40
5	4 x 10	10

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The minimum number of required 60-cell panels the algorithm starts with is 36. The algorithm determines that the optimal number of bins is 40. Five reruns lead to a mean execution time of 15.77 seconds. The positioning and the covering stage were both executed on a Microsoft Surface Book equipped with an Intel Core i7-6600U processor of 2.60 GHz and 16 GB of RAM.

At the beginning of this chapter, the rotation of items was mentioned to be a significant contributor to find an optimal solution. The following table shows the results either with or without the rotation of items:

Table 5-4: Algorithm's result with and without rotation

	Solution with Rotation	Solution without Rotation
All feasible positions for all Items	137	78
Optimal number of required panels	40	46
Execution time [s]	[16.64, 15.64, 15.53, 15.82, 15.23] mean: 15.77	[20.46, 21.25, 20.79, 20.70, 21.02] mean: 20.84

Without rotation, there are much less feasible options to place the items on the panels. With rotation, the number almost doubles from 78 to 137. Both variants start with an initial number of 36 bins. The first feasible and, therefore, optimal solution is 40 with rotation and 46 without rotation. The method without rotation has a higher execution time as more iterations have to be computed even though the execution time per iteration is lower due to less feasible positions. Hence, the inclusion of rotation is significant to obtain an optimal solution.

Translation into a Cutting Lists

Despite the number of required panels, the solver returns a list with all decision variables x_{jk}^i and their values 0 or 1. As mentioned before, the list is very long and very inconvenient to read. Therefore, another Python function is programmed to check all decision variables. If the value equals one, the related row j of the vast C_matrix for each sheet k is stored in a particular two-dimensional subset $k_set[k]$. It is a list that contains a list for all items in sheet k .

Afterward, each sheet's list is used to create a 6×10 matrix that shows the arrangement of items on each sheet. The integer numbers indicate the cutting order and are not relatable to the index of the demanded items. Zeros indicate a trim loss. The following figure shows the cutting arrangement for the first four bins.

sheet 0	sheet 2
<code>[[0 0 0 0 0 3 3 3 3 3]</code>	<code>[[2 2 2 2 2 2 2 2 1 1 1]</code>
<code>[1 1 1 0 0 3 3 3 3 3]</code>	<code>[2 2 2 2 2 2 2 2 1 1 1]</code>
<code>[1 1 1 2 2 2 2 2 2 2]</code>	<code>[2 2 2 2 2 2 2 2 1 1 1]</code>
<code>[1 1 1 2 2 2 2 2 2 2]</code>	<code>[2 2 2 2 2 2 2 2 1 1 1]</code>
<code>[1 1 1 2 2 2 2 2 2 2]</code>	<code>[0 0 3 3 3 3 3 3 1 1 1]</code>
<code>[1 1 1 2 2 2 2 2 2 2]]</code>	<code>[0 0 3 3 3 3 3 3 0 0 0]]</code>
sheet 1	sheet 3
<code>[[2 2 2 2 2 2 2 1 1 1]</code>	<code>[[3 3 3 3 3 3 3 3 3 3]</code>
<code>[2 2 2 2 2 2 2 1 1 1]</code>	<code>[3 3 3 3 3 3 3 3 3 3]</code>
<code>[2 2 2 2 2 2 2 1 1 1]</code>	<code>[3 3 3 3 3 3 3 3 3 3]</code>
<code>[2 2 2 2 2 2 2 1 1 1]</code>	<code>[3 3 3 3 3 3 3 3 3 3]</code>
<code>[0 0 3 3 3 3 3 1 1 1]</code>	<code>[1 1 1 1 1 2 2 2 2 2]</code>
<code>[0 0 3 3 3 3 3 0 0 0]]</code>	<code>[1 1 1 1 1 2 2 2 2 2]]</code>

Figure 5-4: Extraction of the Cutting Stock Program's Final Output

Outlook

In chapter four, the case of damaged solar panels is described, and opportunities to identify those damages are introduced. That knowledge can be implemented in the solver algorithm by creating a matrix referring to the solar panel matrix that indicates damaged cells. An additional constraint could omit damaged areas while searching for feasible positions on the panel.

Chapter 6

6 Conclusion

Within chapter six, a brief summary with all critical information, findings, and results is given. Additionally, the results are discussed, and some outlooks for further studies are presented.

6.1 Summary and Conclusion

Solar energy provided by PV panels experiences significant and continuous growth, as numbers and facts presented in chapters one, two, and three show. That makes solar energy a major contributor to renewable and sustainable energy all over the world. However, there are always two sides to the coin. Proper end-of-life management is crucial to keep solar energy sustainable and environmentally conscious.

The analysis of state-of-the-art recycling or disposal regulations in the U.S. in general, the New England region and Rhode Island itself show a critical lack of end-of-life concerns. While some states are starting to think ahead and enacting product stewardships, recycling programs, or at least end-of-life management regulations, there are no federal laws to provide structures and guidelines for standard handling of solar panel waste. Some states mention the missing volumes of discarded solar panels or absent market need causing the lack of regulations and recycling structures.

While recent studies forecast the amount of solar panel waste based on the technical lifetime of 25 to 30 years, other crucial factors influence waste amounts. Those factors probably will lead to more rapid waste volume growth than expected. In chapter four, the break-even analysis for replacing solar panels reveals a cost-effective replacement after

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eight years, depending on several input data. That is mainly caused due to the growing efficiency gap between installed solar panels and new solar panel technologies (see section 4.2.2). Finally, it will lead to significant amounts of early replacements, and thus, the amount of discarded solar panels will grow much more rapidly than expected.

The majority of discarded solar panels will still be in good condition. On the one hand, most solar panels will be much less than 25 years old and, therefore, long before their warranted lifetime. On the other hand, publications cited in chapters two and four show reasonable power output of solar panels older than 25 years. Even damaged solar panels still generate appropriate amounts of electricity, as the experimental results reported in chapter 4 display. That is demonstrated by repurposing a 17-years old Panasonic monocrystalline silicon solar module. A subpart, almost one-third the area of the original panel size, has been cut out and supplied with a new aluminum frame. The solar cells have been reconnected to form a connected string with a power output of almost 90 watts. Eventually, a 12 V battery and mobile device have been successfully charged by applying a state-of-the-art solar charge controller to the repurposed solar panel (see subchapter 4.3). The resizing not only provides the right power and voltage levels but also makes the solar panel easier to handle.

Further, the experiments reveal damage within the crystalline silicon wafers that might occur when the solar panel's front glass gets hit. While the entire glass shatters, microcracks could appear everywhere within the silicon wafers. Though, bigger cracks visible to the naked eye mainly occur in the closer area around direct impact marks on the glass. However, even with big cracks and probably many microcracks, the solar panels still produce a reasonable share of their original power output – almost 83% (see subchapter

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4.3). That leads to the assumption that solar panels are more durable than commonly expected.

A potential upscaling for the repurposing of standard-size solar panels into smaller, individual sizes would require an optimized cutting strategy. The cutting stock algorithm is the best suitable mathematical problem related to that application and is analyzed in chapter five. The methodology of a two-dimensional bin packing problem is reported first and then transformed into a two-dimensional cutting stock algorithm for the underlying problem. Eventually, the methodology's implementation in Python is stated. As a result, the program finds the minimum number of standard-sized solar panels needed to fulfill a specific demand for individual-sized solar panels. The result displayed by the algorithm is a cutting pattern for each standard-sized solar panel (see section 5.2.3). Additionally, solar panels' damaged areas mentioned above could be omitted by the algorithm.

6.2 Discussion and Outlook

First and foremost, the experimental part within the underlying study can be seen as fundamental research for solar panels' second-life in either way – remanufacturing and repurposing of used solar panels. Hence, some follow-up questions came up during the experiments that are discussed in the following paragraphs.

First of all, the cutting experiments with tempered glass confirm the common knowledge about its cutting behavior with traditional cutting technologies. The whole glass shatters as soon as the physical or thermal stress gets too high, which occurs a few moments after touching the tempered glass with the diamond cutting wheel. A follow-up study could investigate the cutting of tempered glass with a powerful laser cutting machine.

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Shattered front glass on solar panels is not a problem when the whole surface can be appropriately resealed. There might be several methods and materials available that have to be investigated in future experiments. Further, additional studies are needed to prove the long-term resistance and durability of those resealing methods. If resealing is a proper solution for solar panels with shattered front glass, the shattering during the cutting process will not matter, and the cutting process will be much easier and cheaper.

However, the research on new types of solar panel technologies continues, and innovations will occur in the future. A few years ago, half-cut solar cells were entering the market. Solar panels made of half-cut solar cells are supposed to have higher efficiency and power output. [120] As a result, new solar panel types must be reviewed and tested whether remanufacturing and repurposing would still be feasible.

In conclusion, second-life is a feasible and necessary chance for solar panels not to end as solid waste in landfills worldwide. However, additional research is needed to investigate the business potential of second-life applications.

7 Appendices

7.1 Break-Even Analysis for Solar Panel Replacement

period	actual efficiency	new panel's efficiency	gap efficiency	electricity price [\$/kWh] on average	excess revenue [\$/sqm/year]	excess revenue cumulative [\$/sqm/year]	cost of new panels [\$/W]	replacement costs [\$/sqm] depend on efficiency and price per W	replacement costs incl. Subsidies (26% on average)	years, until replacement is amortized (w/o subsidies)	years, until replacement is amortized (with subsidies)
0	16.00%	16.00%	0.00%	\$ 0.24	\$ -	\$ -	\$ 0.70	\$ 112.00	\$ 82.88		
1	15.76%	16.70%	0.94%	\$ 0.25	\$ 2.34	\$ 2.34	\$ 0.68	\$ 113.39	\$ 83.91	48.4	35.8
2	15.52%	17.40%	1.88%	\$ 0.26	\$ 4.86	\$ 7.21	\$ 0.66	\$ 114.60	\$ 84.81	23.6	17.4
3	15.29%	18.10%	2.81%	\$ 0.27	\$ 7.56	\$ 14.77	\$ 0.64	\$ 115.64	\$ 85.57	15.3	11.3
4	15.06%	18.80%	3.74%	\$ 0.28	\$ 10.46	\$ 25.22	\$ 0.62	\$ 116.50	\$ 86.21	11.1	8.2
5	14.84%	19.50%	4.66%	\$ 0.29	\$ 13.55	\$ 38.78	\$ 0.60	\$ 117.22	\$ 86.74	8.6	6.4
6	14.61%	20.20%	5.59%	\$ 0.30	\$ 16.87	\$ 55.65	\$ 0.58	\$ 117.78	\$ 87.16	7.0	5.2
7	14.39%	20.90%	6.51%	\$ 0.31	\$ 20.41	\$ 76.06	\$ 0.57	\$ 118.21	\$ 87.47	5.8	4.3
8	14.18%	21.60%	7.42%	\$ 0.33	\$ 24.19	\$ 100.25	\$ 0.55	\$ 118.50	\$ 87.69	4.9	3.6
9	13.97%	22.30%	8.33%	\$ 0.34	\$ 28.23	\$ 128.48	\$ 0.53	\$ 118.67	\$ 87.82	4.2	3.1
10	13.76%	23.00%	9.24%	\$ 0.35	\$ 32.53	\$ 161.00	\$ 0.52	\$ 118.73	\$ 87.86	3.7	2.7
11	13.55%	23.70%	10.15%	\$ 0.37	\$ 37.11	\$ 198.11	\$ 0.50	\$ 118.67	\$ 87.81	3.2	2.4
12	13.35%	24.40%	11.05%	\$ 0.38	\$ 41.99	\$ 240.10	\$ 0.49	\$ 118.51	\$ 87.70	2.8	2.1
13	13.15%	25.10%	11.95%	\$ 0.39	\$ 47.18	\$ 287.28	\$ 0.47	\$ 118.25	\$ 87.51	2.5	1.9
14	12.95%	25.80%	12.85%	\$ 0.41	\$ 52.70	\$ 339.97	\$ 0.46	\$ 117.90	\$ 87.25	2.2	1.7
15	12.75%	26.50%	13.75%	\$ 0.43	\$ 58.56	\$ 398.53	\$ 0.44	\$ 117.47	\$ 86.93	2.0	1.5
16	12.56%	27.20%	14.64%	\$ 0.44	\$ 64.79	\$ 463.32	\$ 0.43	\$ 116.95	\$ 86.55	1.8	1.3
17	12.37%	27.90%	15.53%	\$ 0.46	\$ 71.40	\$ 534.72	\$ 0.42	\$ 116.36	\$ 86.11	1.6	1.2
18	12.19%	28.60%	16.41%	\$ 0.48	\$ 78.42	\$ 613.14	\$ 0.40	\$ 115.71	\$ 85.62	1.5	1.1
19	12.01%	29.30%	17.29%	\$ 0.50	\$ 85.86	\$ 699.00	\$ 0.39	\$ 114.98	\$ 85.09	1.3	1.0
20	11.83%	30.00%	18.17%	\$ 0.52	\$ 93.75	\$ 792.75	\$ 0.38	\$ 114.20	\$ 84.51	1.2	0.9
21	11.65%	30.70%	19.05%	\$ 0.54	\$ 102.11	\$ 894.86	\$ 0.37	\$ 113.36	\$ 83.88	1.1	0.8
22	11.47%	31.40%	19.93%	\$ 0.56	\$ 110.96	\$ 1,005.82	\$ 0.36	\$ 112.46	\$ 83.22	1.0	0.8
23	11.30%	32.10%	20.80%	\$ 0.58	\$ 120.33	\$ 1,126.16	\$ 0.35	\$ 111.52	\$ 82.52	0.9	0.7
24	11.13%	32.80%	21.67%	\$ 0.60	\$ 130.26	\$ 1,256.41	\$ 0.34	\$ 110.53	\$ 81.79	0.8	0.6
25	10.97%	33.50%	22.53%	\$ 0.62	\$ 140.75	\$ 1,397.16	\$ 0.33	\$ 109.51	\$ 81.03	0.8	0.6

7.2 2D CSP Python Code

```
In [ ]: 1 import numpy as np
        2 from docplex.mp.model import Model
        3
```

Input data

```
In [ ]: 1 #def Input_data(W, H):
        2 # W=Width stock sheet, H = Height stock sheet
        3 W = 10
        4 H = 6
        5
        6 #demanded items h_i * w_i and demand d_i
        7 items_I = np.array([[3, 5],[6, 2],[4, 7],[2, 5],[4,10]],dtype= 'int32')
        8 item_demand = np.array([24,10,30,40,10])
        9
        10 # create cartesian grid for stock sheet
        11 # index in stockgrid corresponds to column in C-matrix
        12 stockgrid = np.arange((H*W)).reshape(H,W)
        13 #print(stockgrid, "\n")
        14
        15 # create correspondence matrix C[j,p]
        16 C_init = np.zeros((0,(H*W)),dtype= 'int32') #empty C matrix at beginning
        17 # subset matrix T(i)
        18 subsetT_i=[]
        19
```

Positioning with Rotation by 90°

```
In [ ]: 1 j = 0 # j refers to row in C-Matrix, set to zero for beginning
        2 set_j=[]
        3 i_count = 0 # counter for item in items_I
        4
        5 for item in items_I: # for all items in items_I
        6     # calculate width and height of item i
        7     wi = items_I[i_count,1]
        8     hi = items_I[i_count,0]
        9     #print(item)
        10    # prove the width of item
        11    for l in range(0,W): # l = 0 is start position in cartesian grid of stock sheet
        12        if l+wi <= W:
        13            # prove the height of item
        14            for h in range(0,H):
        15                if h + hi <= H:
        16                    # add a row to C_matrix
        17                    C_matrix = np.zeros((1,(H*W)),dtype= 'int32')
        18                    C_matrix = np.vstack((C_init, C_matrix))
        19
        20                    # get position index
        21                    for x in range(l, (l+wi)):
        22                        for y in range(h, (h+hi)):
        23                            p = stockgrid[y,x]
        24                            C_matrix[j,p] = 1
        25
        26                    #store C_matrix in C_init
        27                    C_init = C_matrix
        28                    #store row index j in subset T(i)
        29                    set_j.append(j)
        30                    #increase j
        31                    j += 1
        32
        33    #ROTATION
        34    if hi != wi:
        35        # prove the width of rotated item
        36        for l in range(0,W):
        37            if l+hi <= W:
        38                # prove the height of rotated item
```

Appendices

```
39         for h in range(0,H):
40             if h + wi <= H:
41                 # add a row to C_matrix
42                 C_matrix = np.zeros((1,(H*W)),dtype= 'int32')
43                 C_matrix = np.vstack((C_init, C_matrix))
44                 # get position index
45                 for x in range(1, (1+hi)):
46                     for y in range(h, (h+wi)):
47                         p = stockgrid[y,x]
48                         C_matrix[j,p] = 1
49                 #store C_matrix in C_init
50                 C_init = C_matrix
51                 #store row index j in subset T(i)
52                 set_j.append(j)
53                 #increase j
54                 j += 1
55
56         #append set_j of i to subsetT_i
57         subsetT_i.append(set_j)
58         set_j=[]
59         #print(C_matrix)
60         #print(subsetT_i)
61         # i counter plus 1
62         i_count += 1
63
```

Get minimum number of bins K

```
In [ ]: 1 def getK():
2         i=0
3         sumA=0
4         for item in items_I:
5             sumA += (items_I[i,0]*items_I[i,1]*item_demand[i])
6             i += 1
7         return np.ceil(sumA / (H*W))
```

Covering

```
In [ ]: 1 from pulp import *
2         import time
3         model = LpProblem("CoveringAlgorithm", LpMinimize)
```

```
In [ ]: 1 start = time.time()
2
3         K_Number = getK()
4         # create decision variables
5         # x with indizes i, j, k
6         # get number of items
7         i_index = np.arange(np.shape(items_I)[0])
8         print(i_index)
9         # get min # of bins K to enumerate k
10        k_index = np.arange(K_Number, dtype='int32')
11        print(k_index)
12        # get number of rows = positions
13        j_index = np.arange(np.shape(C_matrix)[0])
14        print(j_index)
15        # get point index p in c_jp
16        p_index = np.arange(np.shape(C_matrix)[1])
17        print(p_index)
18
19
```

Appendices

```
20 decision_var = LpVariable.matrix("X_kij",
21                                 [(k,i,j) for k in k_index
22                                   for i in i_index
23                                   for j in j_index], 0, 1, LpBinary)
24
25 var_matrix = np.array(decision_var).reshape(int(K_Number),np.shape(items_I)[0],
26                                             np.shape(C_matrix)[0])
27
28
29 #OBJECTIVE
30 model += lpSum(0)
31
32 #CONSTRAINTS
33 #(1)
34 for k in k_index:
35     for p in p_index:
36         model += lpSum(var_matrix[k, i, j] * C_matrix[j,p] for i in i_index
37                       for j in subsetT_i[i]) <= 1
38
39 #(2)
40 for i in i_index:
41     model += lpSum(var_matrix[k,i,j] for j in subsetT_i[i] for k in k_index) >= item_demand[i]
42
43 # solve the problem with default solver
44 status = model.solve()
45
46 if model.status == 1:
47     print(f"status: {model.status}, {LpStatus[model.status]}\n")
48     print(f"objective: {model.objective.value()}\n")
49
50     for var in model.variables():
51         print(f"{var.name}: {var.value()}\n")
52
53     for name, constraint in model.constraints.items():
54         print(f"{name}: {constraint.value()}\n") #use {if there are several values}
55
56 else:
57     print("no solution found vor ",K_Number,"of bins")
58     K=K
59     #while loop until an optimal solution is found
60     while model.status == 0 or model.status == -1:
61         K = K + 1
62         print(K)
63         new_decision_var = LpVariable.matrix("X_kij",
64                                             [(K,i,j) for i in i_index
65                                               for j in j_index], 0, 1, LpBinary)
66
67         new_var_matrix = np.array(new_decision_var).reshape(1,np.shape(items_I)[0],
68                                                             np.shape(C_matrix)[0])
69
70
71         var_matrix = np.vstack((var_matrix,new_var_matrix))
72
73         #CONSTRAINTS
74         # delete all previous added constraints
75         for item in [item for item in model.constraints]: del model.constraints[item]
76
77         #new number of bins for next iteration
78         bins=K+1
79         k_index = np.arange(bins, dtype='int32')
80         #(1) CONSTRAINT
81         for k in k_index:
82             for p in p_index:
83                 model += lpSum(var_matrix[k, i, j] * C_matrix[j,p] for i in i_index
84                               for j in subsetT_i[i]) <= 1
85
86         #(2) CONSTRAINT
87         for i in i_index:
88             model += lpSum(var_matrix[k,i,j] for j in subsetT_i[i]
89                           for k in k_index) >= item_demand[i]
90
91         # solve the problem with default solver
```

Appendices

```
92     status = model.solve()
93
94     if model.status == 1:
95         print(bins," are used to fit all items")
96         end = time.time()
97         print("time needed for execution",end-start,"\n\n")
98         print(f"status: {model.status}, {LpStatus[model.status]}\n")
99         print(f"objective: {model.objective.value()}\n")
100
101         for var in model.variables():
102             print(f"{var.name}: {var.value()}")
103
104         for name, constraint in model.constraints.items():
105             print(f"{name}: {constraint.value()}")
106         print("time needed for execution",end-start)
107
108     else:
109         print("solver status", model.status)
110         print("no solution for k = ",bins,"bins")
```

Translation into a Cutting List

```
In [ ]: 1 # a subset of C_jp with all j's per bin k
2 k_set=[]
3
4 for k in k_index:
5     used_rows=[]
6     for i in i_index:
7         for j in j_index:
8             if var_matrix[k,i,j].varValue == 1:
9                 used_rows.append(C_matrix[j].tolist())
10 k_set.append(used_rows)
11
12 k=0
13 for list in k_set:
14     print(k)
15     for item in k_set[k]:
16         print(item)
17     k+=1
18
```

```
In [ ]: 1 # create the cutting List per bin k
2 k=0
3 for list in k_set:
4     cuttinglist = np.zeros((H,W), dtype='int32')
5     i=0
6     count=0
7     print("sheet", k)
8     for item in k_set[k]:
9         count+=1
10         matrix=np.array(k_set[k][i]).reshape(6,10)*count
11         cuttinglist = np.add(cuttinglist,matrix)
12         i+=1
13     print(cuttinglist)
14     k+=1
```

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